Introduction to building technology
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1 Building technology

1.1 Introduction

Types of buildings

Just by looking at a cityscape you can see that it consists of various different types of buildings. Essentially there are residential, office, administration, school and factory buildings, theaters, sports arenas and hospitals.

All these buildings have one thing in common. They are supposed to protect its users from external influences, provide security inside and out and ensure a pleasant atmosphere.

The people living in industrialized nations spend 95% of their lives in buildings. This is why the quality of the inside world of buildings is of such importance, concerning health and well-being. The significance of well-being has only recently been detected, when complaints about building-related ailments and symptoms considerably increased. The reasons for this deficit in well-being in indoor spaces are multifaceted, some are objectively detectable, but many “disturbances” depend on the daily routine and social environment of an individual.

Indoor air quality

Some of the objective reasons are for example bad indoor air quality, room temperature or humidity that is either too high or too low, air stream gradients or inconvenient lighting. The human need for comfort doesn’t end with the individual home or workplace. Thus, shopping centers, exhibit halls, sports arenas, fitness centers, museums and theaters are buildings which combine acceptance with the experienced indoor air quality. The individual experience of the buildings and indoor comfort contributes greatly to our well-being.

Building automation

The basis of a good building performance nowadays is modern measuring and control technology in combination with building automation – so to say a harmonious synergy of a building’s architecture, plant engineering and indoor comfort. Despite the fact that most of the processes have been automated, the primary goal of modern building concepts is the possibility for an individual to intervene if necessary.
1.2. Building security

Climatic security

The function of a building envelope from a climatic point of view is that of a buffer between the
controlled indoor climate and the environmental influences of the seasons such as differences in
temperature and humidity (+/-), solar radiation, wind, rain, frost and snow.

Especially the possible combinations of these external influences such as wind and rain, solar
radiation and heat or solar radiation and cold have to be taken into account.

The construction of the building envelope has to be oriented to these weather-related influences as
well as able to “react” with help of the building technology. Depending on the location, the building
envelope has to protect from additional noise pollution caused by road traffic, railways, airplanes and
possibly industries.

![The building envelope protects from weather-related influences and noise pollution](image)

Security

Apart from this, the residents or tenants of a building want protection against trespassing or burglary.
Another crucial function of the building envelope ultimately is sufficient protection against fire.

Energy

Due to the environmental demand for ecological energy consumption for heating and cooling
purposes in a building, considerable improvement of insulation in the building envelope was made.
During that time, a completely stationary approach to the heat transfer through the building envelope
was developed. Even though the heat transfer coefficient (U-value) indicates the specific energy loss,
it doesn’t state the performance of the heat storage of the building envelope, which contains a
considerable potential to conserve energy if used systematically.

For example, if you go by the statistically proven fact, that the average daytime temperature in the
Swiss midland never rises beyond +22°C, you have to remember to compensate the high daytime
temperatures with the cool nighttime temperatures. In modern office or school buildings, which aren’t
used during the night, you can cool the building from the inside by means of forced ventilation using
the cool night air or by using a thermo active building system (TABS). If the building has sufficiently
dimensioned storage mass (concrete, masonry), the inside of the building stays cool, without the
need of additional refrigeration systems, even during the hottest part of daytime. This cooling effect
can even be sustained through shading devices, which should protect the whole of the exterior
building façade from direct sunlight, not only the windows.

We are already able to recognize the technical installations, which can vary depending on the type of
building and its use.
1.3. Building technology

Buildings include extensive technical infrastructures and their complexity is constantly increasing. The term building technology stands for all firmly installed technical systems in- and outside of buildings, which serve the functional operation and the general utilization of these buildings. Essentially, building technology incorporates the following systems and installations:

- Heating, ventilating and air conditioning systems (HVAC-systems)
- Heat recovery systems
- Energy supply and distribution
- General interior lighting
- Shading systems (blinds)
- Passenger transport systems (elevators, escalators)
- Automatic doors and gates
- Security systems (fire, trespassing, access)
- Sanitary facilities and installations
- Disposal systems for waste water, exhaust gases, waste material, etc.

Central systems:
1. Air handling system
2. Boiler and heating distribution
3. Chiller, cooling distribution, heat exchanger (roof)
4. Electrical system cabinet

Decentralized HVAC-systems:
5. Room ventilation
6. Floor heating (possibly floor cooling)
7. Cooling ceiling

Other systems and installations:
8. Lighting system
9. Shading system
10. Weather station
11. Audio/video systems
12. Fire alarm system
13. Surveillance system
14. Access control
15. Transport system
16. Building automation system and technical building management

Fig. 1-3 Technical installations in a building
Hoewever, it does not include production facilities of any kind or technical installations, which are directly used in work processes. The synergy and mutual influence of individual systems plays a growing role. Especially the building envelope isn’t treated as a given, fixed object anymore. It is now adapted to the various operating conditions of building technology.

Tasks of the Heating, ventilating and air conditioning (HVAC systems)

Depending on the purpose of the HVAC systems, the tasks can be divided into two subsections:

- **Comfort systems**
  The term "comfort systems" encapsulates all systems, which create, maintain and ensure an indoor climate for health and efficiency in residential and office buildings, hospitals, restaurants, cinemas, theaters, shopping centers, etc.

- **Industrial systems**
  The term "industrial systems" encompasses all systems, which create, maintain and ensure an indoor climate or conditions for specific production processes, conservation and maturation processes

**Heating technology**

The goal of heating technology is to create a constant, comfortable indoor temperature during the whole heating period. It delivers the heating water for indoor heating and supplies the hot water in various other systems. The heating technology of a building essentially entails the following sections: heat production, heat distribution and heat consumption (e.g. emission to the rooms).

The heat production is a very complex subsection of the heating technology. There are many different kinds of heat generating systems that are used next to oil, gas or wood heat boilers, such as heat pumps, cogeneration plants, solar energy or a combination of the mentioned heat generators (multivalent heat generation) as well as district heating transfer station.

**Ventilation technology**

The ventilation technology is the renewal of ambient air, especially in buildings in which the air is used up or polluted at a fast pace, such as cinemas, theaters, restaurants or in manufacturing facilities. Because the building envelope in today’s commercial and residential buildings is better insulated and more air-tight, mechanical air renewal is required. During the heating period, the indoor temperature has to be kept at the desired level despite the supply of outside air. The outside air is heated by means of heat recovery and heating coils in the air handling unit. The demand for cooling of the renewal air is increasing as the heat gains need to be discharged systematically from the rooms, because of the improved construction of the building envelope.

**Air conditioning technology**

Our well-being and performance is not only influenced by the room temperature but also by how humid, pure and fresh the air is; meaning it has to be an indoor climate which is specifically adjusted to our organism and our perception. These factors can be influenced via air conditioning. The air treatment starts in the air filter then continues on to the air heater, air cooler and ultimately on to the humidifier and dehumidifier. The goal of air conditioning technology of today is mainly the air conditioning for office buildings, shopping centers, airports, cinemas, theaters, etc.

**Refrigeration technology**

Refrigeration technology is becoming increasingly important as the need for buildings to be cooled has multiplied, as per the reasons mentioned above. As a result, the use of cooling sources which are available in nature (e.g. cool outside air, surface water) play an increasingly critical role as does the energetically appropriate use of refrigeration plants and of environmentally friendly refrigerants.
1.4. Building automation

Depending on the intended purpose of a building, it is possible that the building technology has to meet different demands. There are generally three primary demands, though, that reappear consistently:

- The needs of a person for well-being and comfort in a building envelope need to be oriented to the specific type of use and be met regardless of external influences.
- Protection and safety calculated to specific risks for residents of and material assets in a building need to be warranted in case of fire, water or technical damage, or intrusion from third parties.
- These demands need to be met with sustainable investment and minimal follow-up costs for energy, service and maintenance.

To meet the aforementioned demands, the relevant building installations are required. It may be referred to as intelligent building technology, when synergies of these technological installations with regard to specific requirements for use with help from building automation are realized.

Planning of building technology

Only the technically practical building technology, i.e. useful and environmentally friendly is to be implemented, as opposed to everything technically possible. Thus the planning phase is paramount, wherein all the local conditions are taken into account and all demands are carefully scrutinized. To plan a conceptually correct building technology requires a high level of basic knowledge of the connections between building engineering physics, thermodynamics, fluid mechanics, chemistry and ecology. Intelligent building technology requires experienced planners, who are proficient in interdisciplinary integral planning methods and consistently use them.

Building automation systems

Appropriate systems and equipment, as well as certified functions and applications are required as a solution to control tasks. Nowadays, the various components are mostly interconnected via standardized communication systems such as BACnet, KNX, Modbus, etc. The building technology can thereby ensure an optimized operation which always complies with the desired user comforts.

Fig. 1-4  Communicatively connected systems and equipment in a building and beyond allow for an efficient and optimized operation
1...4 Operation and coordination of central building technology plants
5...7 Operation and coordination of decentral building technology plants
with retroactive effect (demand management) on central building technology plants
8...9 Operation and coordination of lighting and shading systems
also in alignment with heating, ventilation and air conditioning systems
10 Weather station for optimal operation of building technology plant
but also for security functions (e.g.: wind warning for shading systems,…)
11 Integration of the audio and video systems in operation and control concept of rooms
(e.g.: scene control in conference rooms)
12...14 Integration of building and personnel safety system
15 Operation and control of transportation systems
16 Operation, control, surveillance with supervisory building management station
via integration of all building technology plants
2 Physical principles

2.1. Introduction

From the extensive field of physics, we will cover the application of thermodynamics and hydrodynamics, with reference to the area of Heating, Ventilation and Air-conditioning (HVAC) systems in this chapter. In addition, we will also be engaged with the hygienic fundamentals of HVAC systems, in particular with the subject of “comfort”. As an introduction, we would like to define the terms used:

- **Thermodynamics**: Section of physics where the behaviors of physical systems involving supply or delivery of heating energy are investigated along with temperature changes. The fundamentals of thermodynamics are specified by the Laws of Thermodynamics.

- **Hydrodynamics**: Section of fluid mechanics involved with the flow of incompressible materials, that is, mainly with flowing fluids. Flows having considerable density variations are covered in gas dynamics. At the limit, for static fluids, hydrodynamics reduces to hydrostatics.

**SI units**

The name “Système International d’Unités” (International System of Units) and the abbreviation SI were adopted by the 11th General Conference for Mass and Weights in 1960. SI units comprise the seven basic units and derived units with a factor of unity.

<table>
<thead>
<tr>
<th>Basic Unit</th>
<th>SI Basic unit</th>
<th>Name:</th>
<th>Symbol:</th>
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<tr>
<td>Length</td>
<td>meter</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Mass</td>
<td>kilogram</td>
<td>kg</td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td>second</td>
<td>s</td>
<td></td>
</tr>
<tr>
<td>Electrical current</td>
<td>Ampere</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>Absolute temperature and</td>
<td>Kelvin</td>
<td>K</td>
<td></td>
</tr>
<tr>
<td>temperature difference</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concentration</td>
<td>mole</td>
<td>mol</td>
<td></td>
</tr>
<tr>
<td>Light intensity</td>
<td>candela</td>
<td>cd</td>
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Table 2-1 SI-base units

Derived units are formed by multiplying or dividing the basic units. The same holds for the symbols. Thus, for example, the SI unit for speed is: Meters divided by seconds (m/s).
2.2. Thermodynamics

How is heat generated?
Heat is generated, for example, when a space capsule reenters the earth’s atmosphere at almost 40,000 km/h, 2,000 to 3,000 °C, created from the collision of atoms of air with the heat shield, causes the atoms of the heat shield to oscillate. In this case, heat is produced by friction caused by the loss of the capsule’s kinetic energy. In each material, be it solid, fluid or gas, the atoms or molecules are always in motion, i.e. oscillation (Fig. 2-1). And this is the definition of heat, that is, the oscillation of atoms or molecules: The greater the oscillation, the greater the heat level. When we measure the temperature of a substance, it is these oscillations that we measure.

![Fig. 2-1 Heat is the oscillation of atoms and molecules](image)

State change
If we hold a piece of metal over a flame, we cause the atoms in the metal to be thermally excited. The atoms begin to oscillate strongly and the metal heats accordingly. The metal expands because the oscillatory movements of the atoms reduce their mutual attraction (binding force). If we continue heating, the atoms in the metal lose their intrinsic order: The metal melts and individual atoms even shoot from the surface as vapor, or more exactly, leave the fluidized surface as gas.

We have now become familiar with the three thermodynamic aggregate states:
- solid
- fluid
- gaseous

Radiation
While these oscillations of the atoms or molecules, together with their constant interactions, take place, another process occurs, which we also perceive as heat. As a result of the interactions of the oscillating atoms, individual electrons constantly orbiting the atom nuclei are suddenly flung from their normal orbit to one further out (Fig. 2-2). This condition is unstable, however, and they return to their normal orbit relatively quickly, but in only small “quantum” steps. But so that no energy is lost, they release as much energy in the form of electromagnetic radiation as was required to increase their orbit.

If this radiation strikes other atoms or molecules, e.g. in our skin, then the energy they give up increases the oscillation of the atoms or molecules, which we notice as heat. This radiation, derived from heat and causing heat is referred to as thermal radiation or infrared radiation. It is not visible to the naked eye.

Radiation allows the emission of heat without a material carrier between the heat source and the radiated body. This is, for example, how radiant energy from the sun is transmitted to Earth.
Each warm material radiates thermal energy continually. This also holds for the metal that we heated and also for the flame used to heat it. As soon as we remove the flame, the oscillations of the metal atoms immediately become weaker, the temperature falls and the thermal radiation reduces. Just as the flame thermally excited the metal, now the heated metal excites its cooler surroundings, that is, e.g. the surrounding air and the pliers we use to hold the hot metal. With this process, the metal loses its internal energy until its temperature is in equilibrium with the surrounding temperature. Its atoms, however, at that point are in no way quiescent; rather oscillate with an energy corresponding to this temperature.

Fig. 2-2 Electromagnetic radiation through returned energy of the electrons

The presentation of these concepts of the oscillation of atoms and the leaps of electrons from orbit to orbit allows us to more easily understand the laws of thermodynamics.

**First law of thermodynamics**

The sum of all energy in a closed system is constant. Energy cannot be lost nor be created out of nothing, but can only be transformed into other forms of energy.

**Kinetic energy**

(Formula symbol W) Kinetic energy or momentum is that mechanical energy that a body has because of its movement.

**Nuclear energy**

The binding energy of an atom nucleus (in the true sense) is set free or made useful during a nuclear reaction. On a commercial basis only the energy released by nuclear fission processes in nuclear power plants has been used until now. The impact of atomic particles in an atomic reactor takes place at a very high velocity on unfashionable material.

**Elektromechanical energy**

Is mechanical energy generated by electricity? In heat engines, mechanical or electrical energy is generated from heat.

**Potential energy**

That energy contained in a body or particle, because of its position in a field of force or because of its interactive position with nearby bodies or particles. Potential energy is held e.g. by a raised body, a spring in tension or in the water of a mountain dam. Water power is converted to electrical energy and this, in turn to electric heat, power to drive motors or light from electricity.

The energy of light is stored as chemical energy in the atoms and molecules of organic material. This energy can be released during combustion as heat, light and power.
Mechanical work can be converted to heat. The reconversion of heat into mechanical work is only partially possible. There are always losses.

Heat is created during transformation processes and is simultaneously a form of energy.

**Second law of thermodynamics**

Heat can, of itself, never pass from a body of lower temperature to a body of higher temperature.

A warmer body immediately thermally excites a cooler one and in doing so, loses internal energy. This determines the direction of all heat flows:

**All heat transfer processes always proceed from the warmer to the colder medium.**

The cooling that we detect is never a cold transfer, rather a heat loss of our bodies.

**Temperature**

Apart from pressure, density and specific volume, temperature is the dimension for the thermal state. The oscillation of the atoms in each heated material shows us that the lowest temperature, absolute zero, can only be reached if the atoms no longer move, that is, no longer exhibit the slightest oscillation.

Practically, this point is unreachable, because the smallest heat quantity is sufficient (e.g. from the container or even from the thermometer) to prevent the temperature of the substance from going low enough.

**Celsius**

The *relative temperature scales* (the Celsius and Fahrenheit scales) are based on temperature dependent material characteristics such as the freezing and boiling points of water.

The **Celsius-Scale** was developed by the Swedish astronomer Anders Celsius in 1742. (*1701, †1744)*

The Celsius scale is the most commonly used in general daily measurements of temperature (e.g. room or outdoor temperature).

The calibration points are:

- 0 °C = freezing point of water
- 100 °C = boiling point of water

at the standard air pressure of 1,013 mbar.

The absolute temperature *Theta* is based on absolute zero according to Kelvin and corresponds to -273.15 °C. In physics, the unit for the Kelvin scale is the Kelvin (K)

(Kelvin, British physicist, 1824 – 1907).

**Kelvin**

Relative to the Celsius scale 0 °C = 273 K and accordingly

\[ n \text{ K} = 273.15 + n \, ^\circ \text{C} = \text{absolute temperature T in Kelvin} \]

Temperature differentials \( \Delta \theta \) (delta theta) are also specified in Kelvin.

Temperature can be measured by using the thermal expansion of solid materials (mostly metals), the thermal expansion of liquids (e.g. alcohol in a thermometer), or by changes in electrical resistance (see under "Measuring Systems").
Fig. 2-3 Temperature scales for °C, K, °F

Zero point: 0 °C = 273.15 K = 32 °F

Degrees Celsius to Kelvin: K = °C + 273.15

Degrees Celsius to degrees Fahrenheit: °F = °C \cdot \frac{9}{5} + 32

Comparison and conversion of the various scales

\[ T[°C] = \frac{5}{9} \cdot (T[°F] - 32) / 0.55 \cdot (T[°F] - 32) \]
\[ T[°F] = \frac{9}{5} \cdot T[°C] + 32 / 1.8 \cdot T[°C] + 32 \]

Example:
10 °C \Rightarrow 283.15 K \Rightarrow 50 °F

When calculating with temperatures in reports, communications and writings, we designate a specific temperature with the Grecian letter \( \theta \) ("theta", previously often shown with \( J \)).

Thus, for example, \( \theta = 7 °C \). Frequently \( t = 7 °C \) is also written. As long as only temperature is involved, this would be acceptable. As soon as the time \( t \) becomes involved with a momentary consideration, formula or calculation, however, the possibility for mistakes increases.

If we are involved with specific temperature, then \( \theta \) receives index letters. These are normally the leading letters of the associated term:

\( \theta_{\text{DA}} \) (theta indoor air), \( \theta_{\text{ODA}} \) (theta outside air)

Different temperatures in a room, a boiler or along a surface are numbered.

The average (mean) temperature of a number of temperatures is designated as \( \theta_m \).

A temperature differential is designated as \( \Delta \theta \) (delta theta) in Kelvin (K).
2.2.1. Thermal expansion of solid materials

Thermal expansion

All substances, whether solid, liquid or gaseous, expand upon heating (energy supply). The amount of expansion, however, varies. This thermal expansion is associated with powerful forces. Bridges, for example, must be set on bearings and possess expandable joints, so that they do not crack in winter and do not destroy their supports in summer.

Let us first compare how strongly and differently a steel rod of 1 m length and a copper rod of the same length expand upon heating:

Linear expansion

<table>
<thead>
<tr>
<th>Temperature difference</th>
<th>Steel</th>
<th>Copper</th>
</tr>
</thead>
<tbody>
<tr>
<td>-100 °C to 0 °C</td>
<td>+1.67 mm</td>
<td>+2.65 mm</td>
</tr>
<tr>
<td>0 °C to 100 °C</td>
<td>+1.20 mm</td>
<td>+1.65 mm</td>
</tr>
<tr>
<td>100 °C to 200 °C</td>
<td>+1.31 mm</td>
<td>+1.73 mm</td>
</tr>
<tr>
<td>200 °C to 300 °C</td>
<td>+1.41 mm</td>
<td>+1.77 mm</td>
</tr>
<tr>
<td>300 °C to 400 °C</td>
<td>+1.52 mm</td>
<td>+1.92 mm</td>
</tr>
</tbody>
</table>

Table 2-2 Thermal expansion of steel and copper

We recognize that differing materials expand differently and this in accordance with the linear expansion coefficient \( \alpha \).

The coefficient of linear expansion is the increase in unit length of a body upon a 1 K increase in temperature. This number changes somewhat with temperature increase, so fixed averages are used in calculations.

<table>
<thead>
<tr>
<th>Body</th>
<th>( \alpha ) mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron (Fe)</td>
<td>1.23</td>
</tr>
<tr>
<td>Aluminum (Alu)</td>
<td>2.38</td>
</tr>
<tr>
<td>Platinum (Pt)</td>
<td>0.9</td>
</tr>
<tr>
<td>Copper (Cu)</td>
<td>1.65</td>
</tr>
</tbody>
</table>

Table 2-3 Thermal expansion of different metals

A 5 m long radiator made of steel expands approximately 0.6 mm per meter upon warming to 50 K, thus it approximately expands by 3 mm (Fig. 2-5). This is a considerable amount. The radiator expands this much each morning in winter when the heating system switches from reduced night operation back to full output, becoming some 50 K warmer in the process in a few minutes.
Fig. 2-5 Thermal expansion of a steel radiator

If the radiator is fixed in place so that it cannot glide freely, the familiar cracking sounds are heard when the radiator is expanding. In poorly controlled systems, where the radiator temperature continually oscillates, the cracking can be heard the entire day.

**Bimetallic elements**

Thermal expansion of materials not only provides the engineer with difficulties, it also can be utilized technically: In a bimetallic element, two metals of different linear expansion are soldered together (Fig. 2-6). If this "sandwich metal" (1) is heated, it is forced to bend because one side expands more than the other. Also, the longer the bimetallic element and the higher the temperature, the stronger the bending. If the element is formed in a circle of spiral and supplied with a pointer and appropriately calibrated, the bimetallic element becomes a bimetallic thermometer, (2). If it is supplied with a contact, it becomes a thermal, that is, temperature-dependent switch (3-4).

Such bimetallic switching systems are often used in technical applications: In simple designs as safety switches against excessive temperature (e.g. in motor windings or for motor protection), and in high-quality designs with adjustable switching points as thermostats. The temperature-sensitive bimetallic element is specified as a bimetallic sensor.

If a bimetallic element that, for example, is completely straight at 20 °C is suddenly exposed to a temperature of 50 °C, it immediately begins to bend. The bending stops only when the entire bimetallic element has heated to 50 °C. Under identical conditions, the same time is always required.
Thus the bimetallic element is suitable for manufacturing time switches (4) in an operation that, depending on application, delays or accelerates switching on or off. A small electrical heating resistor can be used to heat the bimetallic element and so accelerate the switching sequence.

Controllers having a solid expansion sensor are related to temperature controllers using bimetallic sensors. The tube and rod used in this construction also consist of two metals having differing expansion coefficients. The switching system is activated by the difference in lengths occurring upon heating.

Thermostats with rod probes (also referred to as immersion sensors) are preferably used as temperature controllers for liquids or gases in storage heaters, boilers, piping, etc. While the medium can wash round the sensor so that it quickly takes on the temperature of the medium, the operating head remains outside the container. This makes it easily accessible and protects it from excessive heating.

2.2.2. Thermal expansion of liquids

The molecular association of liquids is less than that of solids: Liquids expand more upon heating. As for solids though, liquids have differing expansion coefficients and similarly expand more per K at higher temperatures than at lower temperatures.

At constant pressure, the volumetric expansion symbol for liquids and gases is $\beta$ (Beta) [1/K].

Volumetric expansion

<table>
<thead>
<tr>
<th>Liquid</th>
<th>$\beta$ 10^-3/K</th>
<th>Liquid</th>
<th>$\beta$ 10^-3/K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>1.20</td>
<td>Water (20..70 °C)</td>
<td>0.20...0.59</td>
</tr>
<tr>
<td>Fuel oil EL</td>
<td>0.7</td>
<td>Toluene</td>
<td>1.08</td>
</tr>
</tbody>
</table>

Table 2-4 Volumetric expansion coefficient of different liquids

Thermal expansion of liquids is again used for thermometers and in the construction of temperature-dependent switches (Fig. 2-7).

![Fig. 2-7 Thermal expansion of liquids](image)

In the thermometer (1), the liquid in the globe expands upon heating and moves up into the capillary. If the temperature of liquids is to be measured exactly, the entire thermometer including capillary must be immersed into the liquid because the liquid in the capillary also expands.
Thermal switches, that is, thermostats, fitted with a liquid expansion sensing element are, in principle, constructed similarly (2). Sensing element capillary tube, metal enclosure and diaphragm are filled with oil. When the oil expands because of heating, the diaphragm is pushed upwards and activates the switching system.

The diaphragm can activate a valve instead of an electrical switch. The result is a temperature-dependent control valve (3).

2.2.3. The medium “water”

Volume change

Water expands as do all liquids. While others expand more and more from their melting point with each K temperature increase, water first contracts from 0 to 4 °C (the anomaly of water) and only then does it begin to behave in a standard manner, i.e. expand. Here, this is referred to as an anomaly of water.

<table>
<thead>
<tr>
<th>1000 kg water</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1 °C</td>
</tr>
<tr>
<td>0 °C</td>
</tr>
<tr>
<td>2 °C</td>
</tr>
<tr>
<td>4 °C</td>
</tr>
<tr>
<td>10 °C</td>
</tr>
<tr>
<td>20 °C</td>
</tr>
<tr>
<td>30 °C</td>
</tr>
<tr>
<td>40 °C</td>
</tr>
<tr>
<td>50 °C</td>
</tr>
<tr>
<td>60 °C</td>
</tr>
<tr>
<td>70 °C</td>
</tr>
<tr>
<td>80 °C</td>
</tr>
<tr>
<td>90 °C</td>
</tr>
<tr>
<td>100 °C</td>
</tr>
</tbody>
</table>

Table 2-5 Volume change of water depending on the temperature

The table shown above also indicates the level of expansion of water in a central heating system. Assume that just 1,000 liters of water at 20 °C is in a boiler, the piping and the radiators. Also assume that this system in winter is often operated with water at a temperature of 70 °C. This means that there is a volume increase of 21 liters!

These 21 liters must be collected somewhere or else the system will burst. For this purpose, each hot water central heating system has an expansion tank.

Since water expands so strongly, it becomes correspondingly lighter because its density \( \rho \) [kg/m\(^3\)] changes.

Density

*Physics*: (mass density, specific mass) symbol \( \rho \) (rho), the quotient of mass and volume of a body. Besides depending on the material of the body, the density is also dependent on pressure and temperature (especially for gases/liquids).

The SI unit of density is kg/m\(^3\). It is also often indicated as kg/dm\(^3\).
Material Density kg/dm$^3$

<table>
<thead>
<tr>
<th>Material</th>
<th>Density kg/dm$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>2.699</td>
</tr>
<tr>
<td>Concrete</td>
<td>1.5 ... 2.4</td>
</tr>
<tr>
<td>Lead</td>
<td>11.35</td>
</tr>
<tr>
<td>Ice (at 0 ºC)</td>
<td>0.917</td>
</tr>
<tr>
<td>Iron</td>
<td>7.86</td>
</tr>
<tr>
<td>Gold</td>
<td>19.3</td>
</tr>
<tr>
<td>Wood (dry)</td>
<td>0.4 ... 0.8</td>
</tr>
<tr>
<td>Sand (dry)</td>
<td>1.5 ... 1.6</td>
</tr>
<tr>
<td>Foam material</td>
<td>0.02 ... 0.05</td>
</tr>
<tr>
<td>Uranium</td>
<td>18.7</td>
</tr>
<tr>
<td>Water 20 ºC</td>
<td>0.9982</td>
</tr>
<tr>
<td><strong>Water (at 4 ºC)</strong></td>
<td><strong>1.000</strong></td>
</tr>
</tbody>
</table>

Table 2-6 Density of some solids and liquids in kg/dm$^3$ at 20 ºC

Example: At 20 ºC, 1,000 liters of water weighs approx. 1,000 kg and at 90 ºC = approx. 965 kg. Buoyancy changes with density so that less dense material floats on top of the denser material. Thus, heated water always moves upwards and is layered over the colder water. This layering is, for example, very noticeable while swimming in a lake or in the ocean.

![Temperature layers in a boiler](image)

Technically, this lifting effect of heated water was used for gravity heating in older buildings.

In every hot water storage tank the heated (and expanded!) water moves so fast upwards that it only gives up a fraction of its heat to the surrounding cold water (Fig. 2-8). In this way, the hot water collects at the top and is withdrawn there. Cold water enters from the bottom. The temperature layering is so stable that even the swirl of the entering cold water hardly affects it.
The fact that warm water layers over cold water also makes life difficult for us: For example, in indoor swimming pools, we cannot simply supply hot water through an inflow from above or below; that would most surely lead to a temperature stratification. Such stratification would only be very slowly eliminated by the churning movements of the swimmers. Further, measuring the effective water temperature in a pool with temperature stratification is very difficult. In order to get around this problem, systems designed for comfort supply filtered and heated water at many locations along the bottom of the pool.

**Temperature stratification**

The tendency of warmer water to form a layer over colder water is so strong that such stratification even remains preserved in piping over long distances (Fig. 2-9). We have to take this into account when considering the installation locations for temperature sensors or controllers in piping.

![Fig. 2-9 Temperature stratification of flowing water in piping](image)

We have learned that **heat is the oscillation of atoms** or molecules. Heat is a form of energy and the temperature of a material is a measure of how strongly these small building blocks are oscillating. In addition, we have seen that with increasing oscillatory movement (= temperature), the structure of the material relaxes, that it expands and in the end **solids** transform into liquids and **liquids** transform into a **gaseous state**.

**The anomaly of water**

Water has the highest density at 4 °C and expands both when heat is supplied and removed. While other liquids contract when solidifying, water expands in an amount exactly equal to 1/11 of its volume (Fig. 2-10). This is why ice can rupture with enormous force rocks, road surfaces and house facades as well as piping, radiators, etc.

![Fig. 2-10 Volume increase of water upon freezing](image)
Frost damage occurs in heating systems mostly in unused and unemptied systems or if the heating is reduced excessively in winter. In ventilation and air conditioning systems, on the other hand, it is standard that in winter outside air of -10 °C or lower is blown through air heating coils heated with hot water. It is our responsibility to ensure a secure freezing protection function through dependable temperature monitoring, because if the hot water supply stops even for a few minutes in such icy conditions, then expensive frost damage can occur.

**Vaporization**

We now wish to observe the aggregate state of water in somewhat more detail. As we know, water vaporizes. And this has a basis in the movement of molecules: In contrast to solids, the water molecules do not oscillate about fixed points. Because of this, those molecules that find themselves at the surface of the water can easily shoot out from it. Some of these will reenter the water, while the rest remain as invisible water vapor in the air. And each particle that escapes and is carried away by the wind takes its heat of vaporization with it. When this procedure takes place on our skin, we clearly notice the heat loss through this vaporization as a cooling effect.

We take an approximately half filled container of water and cover it (Fig. 2-11). Because of the cover, the air can no longer carry the vaporized water molecules away. A water vapor-air mixture thus forms over the water surface as more and more water molecules vaporize. Water molecules are also returning into the water from the vapor-air mixture. Initially, however, more water molecules on average leave the water surface than return until a dynamic equilibrium situation is finally reached, where the number of water molecules leaving the water surface equals the number returning to the water. We refer to this as air saturated with water vapor.

![Fig. 2-11 Dynamic equilibrium, situation in a closed container of water](image)

If we raise the temperature of the water, the water molecules increase their oscillations and so more can leave the water surface. Initially, again, more water molecules will leave the water surface than return to it until the concentration of the water molecules in the air reaches a level where the number of molecules leaving the water surface equals the number returning. Thus, the higher we raise the temperature, the higher the fraction of water vapor in the vapor-air mixture.

If we heat the water even more, bubbles of hot vapor suddenly appear in the water. The water boils. At this point, the formation of vapor is no longer restricted to the water surface; it also forms within the water. We now keep adding heat to the container so that the amount of steam continually increases (the boiling rate increases although the water temperature remains the same). Eventually, sufficient pressure will built up within the container to lift the cover, allowing some steam to escape (Fig. 2-12). Another way of looking at this is to say that at the same pressure steam needs more volume than water.
Boiling point

At standard air pressure, water boils at 100 °C. What does "standard air pressure" mean?

This definition states that standard air pressure exists if the weight of air at sea level is 101,325 N/m² (or 101.3 kPa = 1013 mbar). Thus, an air column of 1 m² cross section reaching out into space has this weight.

The sentence “At standard air pressure, water boils at 100 °C” means that the boiling temperature is evidently dependent on the pressure over the water. In other words, the higher the pressure on the water, the higher the oscillations required of the water molecules, that is, the higher the temperature needed in order to convert liquid water to steam. We can then draw the conclusion that for pressures above standard, the boiling point will increase. This is also the case: At 1.5 bar (overpressure of 0.5 bar), e.g. in a pressure cooker, water actually does boil at approximately 110 °C (Fig. 2-13).

The boiling point of water, i.e. the temperature where the transition from liquid water to water vapor occurs, is dependent on pressure.
Water temperatures above 100 °C frequently occur in district heating plants. This means that a pressure of more than 1 bar must exist in the piping network to keep the water from boiling.

In the next step, we wish to investigate the amount of energy required to convert ice into water and then into vapor. The relationship is shown in the temperature-enthalpy graph (Fig. 2-15).

In order to heat one liter of water from 0 °C to 100 °C, we need 419 kJ heat.

We determine that the temperature does not remain constant during this process. Sensible (noticeable) heat is being transferred.

At 100 °C, the water spontaneously begins to vaporize creating steam. Were we now to stop adding heat, the water temperature would immediately drop; the internal vaporization would stop, halting the production of steam. In order to completely convert one liter of water to steam, we would have to add heat until no water remained. For this, we need an additional 2,257 kJ which means more than five times the amount of heat required to heat the water from 0 °C to 100 °C.

We determine that the temperature remains constant at 100 °C during this conversion process. Thus, no sensible heat is being transferred; rather what is called the latent heat of vaporization is being consumed in order to change the aggregate state of the water from liquid to gaseous.
As on a theoretically speaking, no energy can be lost, one kilogram of steam at 100 °C thus holds heat energy amounting to $419 + 2,257 \text{ kJ} = 2,676 \text{ kJ}$. This steam is thus said to have a heat content (enthalpy) of 2,676 kJ/kg.

335 kJ are required to convert 1 kg of ice at 0 °C to one liter of water at 0 °C. The temperature also remains constant during this conversion. No sensible heat is detected, but heat is transferred. This heat required to convert solid water to liquid water is designated as the latent heat of fusion.

The state change of water can be represented in various ways.

Fig. 2-15 shows the dependence of temperature on the heat supply at constant pressure. You can clearly locate the areas of sensible and latent heat transmission. The heat content of the water, i.e. its enthalpy, is increased through the addition of heat.

Pressure-temperature or pressure-enthalpy charts, as well as water-steam tables are additional ways of showing these relationships.

**Sensible heat**

Sensible heat is perceptible heat added to a material (e.g. using a burner or an electric heating element). Sensible heat is detectable using a thermometer.

**Latent heat**

Latent heat is the heat added to a material to cause its state to completely change. No temperature change takes place during these conversions.

**Enthalpy**

Enthalpy is the sum of the sensible and latent heat possessed by a substance. If processes are involved having considerable pressure and volume changes (e.g. compression), mechanical work (potential energy) done on the material must be added (units of [kJ/kg]).

With the exception of water’s strange behavior below 4 °C and the fact that each liquid has its own specific coefficient of expansion, everything we have said about water also is applicable to other liquids.
2.2.4. Thermal expansion of gases

If we heat a bar shape of iron, water and air each with a cross section of $1 \text{ cm}^2$ and $10 \text{ cm}$ in length to $100 \text{ K}$ and compare the thermal expansion of the three materials, we obtain the result shown in Fig. 2-16.

![Fig. 2-16 Thermal expansion of iron, water and air](image)

We know why the difference is so large: For iron, the atoms are fixed in place relative to one another, for water the relationship is less distinct and for gases, there is only a very small mutual attractive force among the atoms. The lower the mutual attractive force, the stronger the thermal stimulus (the increased oscillation of the atoms and molecules needs more space).

While solid and liquid materials expand depending on material type, all gases essentially behave the same. The behavior is often expressed in terms of an ideal gas, i.e. a gas that obeys the following laws:

**Boyle-Mariotte and Boyle-Mariotte’s law**

The law discovered by R. Boyle and E. Mariotte: In a given amount of an ideal gas, the product of pressure and volume at constant temperature is a constant

$$p_1 \cdot V_1 = p_2 \cdot V_2$$

Density behaves like the associated pressure.

**Gay-Lussac and Gay-Lussac’s law**

Gay Lusaac-s law describes the principles of the behavior of ideal gases: The volume $V$ increases at constant pressure $p$ linear to the absolute temperature $T$:

$$V_1 = V_0 \cdot (1 + \alpha \cdot T_1) = V_0 + V_0 \cdot \alpha \cdot T_1 \quad (T \text{ in K})$$

The isobaric ($p = \text{constant}$) coefficient of expansion for all ideal gases has the value $\alpha = 1/273 \text{ K}$. ($V_0 =$ volume at $0 \text{ °C}$). Consequently, at constant pressure, the gas volume in question is proportional to the absolute temperature, or,

$$V_1 / V_2 = T_1 / T_2$$

Gases and gas mixtures, such as air, expand $1/273$ of their volume at $0 \text{ °C}$ for each K heating.

($\alpha = 0.00366 \text{ K}^{-1}$)
In other words, 1 m$^3$ (= 1,000 dm$^3$) of air always expands approximately 3.66 dm$^3$ for each increase in temperature of 1 K. Whether it is heated from 0 °C to 1 °C or from 20 °C to 21 °C is, for our purposes, irrelevant.

The more the air expands, the lighter (less dense) it becomes. (The density of air at 0 °C and 1013 mbar = 1.293 kg/m$^3$). The air that we experience as weightless is, in reality, not as light:

\[
\begin{align*}
1 \text{ m}^3 \text{ air at} & \quad 0 \, ^\circ\text{C} \quad = 1.293 \, \text{kg} \\
& \quad 20 \, ^\circ\text{C} \quad = 1.205 \, \text{kg} \\
& \quad 50 \, ^\circ\text{C} \quad = 1.093 \, \text{kg}
\end{align*}
\]

From this we can see that 1 m$^3$ of air, moving past a radiator and heating up from 20 °C to perhaps 40 °C, experiences a

**Buoyancy** of approx. 1 N (N = Newton; explained below)

**Force, physics**: Cause of acceleration or reshaping of a body. The force $F$ is defined as the product of the mass $m$ of a body and the acceleration $a$ experienced by the body, or $F = m \cdot a$

Depending on their physical source, we differentiate among gravitational force, electromagnetic force, strong force (interactive nuclear force) as well as the weak force (leads to the decay of atomic particles). The Newton (N) is the SI unit of force.

A force of 1 N is considerably much for “light” air. Thus, air heated by a radiator moves swiftly upwards and along the ceiling where it gives off its heat to the ceiling and the surrounding air.

In cooling, the air increases in density (becomes “heavy” again); moves lower and eventually reaches the radiator again, “sucked in” by the flow of air constantly moving upward from the radiator (Fig. 2-17).

This means a same gravity circulation effect as for a hot water gravity heating system.

Since the air molecules can move freely, they mix much more easily with one another than molecules in liquids. The result is that there are less sharply delineated temperature layers in gases.
The temperature behavior caused by the gravity circulation within a room is shown in the graph below (Fig. 2-18).

![Graph showing temperature behavior](image)

Fig. 2-18 The relationship between room height and room temperature

We have touched on the subject of “The thermal expansion of gaseous materials.” Knowledge of the other gas laws is predominantly an important prerequisite for ventilation and air conditioning systems.

### 2.2.5. The medium “air“

A thin layer of air surrounds the earth. Variations in this layer cause a changing pressure (barometric reading). Air’s most critical feature is that life forms need it to breath. A grown person, for example, requires approximately 0.5 m$^3$ air to breathe per hour to maintain life processes. In addition, the air fulfills other vital requirements. For example, air absorbs vast amounts of water in form of vapor from the surfaces of lakes and oceans, transports it large distances and then lets it fall to earth in the form of precipitation.

The physical quantities used to describe the state of the air are referred to as variables. Air conditioning systems also deal with these variables. The most important are air temperature, humidity and pressure.

#### Pure dry air

Air is a mixture of gases, vapors and contaminants. Pure, dry air only exists theoretically. It consists of:

<table>
<thead>
<tr>
<th>Gaseous material:</th>
<th>Chemical material:</th>
<th>Volume: %</th>
<th>Weight proportion: %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>N$_2$</td>
<td>78.060</td>
<td>75.490</td>
</tr>
<tr>
<td>Oxygen</td>
<td>O$_2$</td>
<td>20.960</td>
<td>23.170</td>
</tr>
<tr>
<td>Argon</td>
<td>Ar</td>
<td>0.930</td>
<td>1.290</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>CO$_2$</td>
<td>0.030</td>
<td>0.040</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>H$_2$</td>
<td>0.010</td>
<td>0.001</td>
</tr>
<tr>
<td>Neon</td>
<td>Ne</td>
<td>0.002</td>
<td>0.001</td>
</tr>
<tr>
<td>Helium, Krypton, Xenon</td>
<td>He, Kr, Xe</td>
<td>0.008</td>
<td>0.008</td>
</tr>
</tbody>
</table>

Table 2-7 Composition of dry air

In addition to the thermal state of the air, the purity, gas percentages and mainly the water content of the air play a large roll in ventilation and air conditioning systems.
Humidity of the air

The water content of a substance is measured by moisture content or humidity. In the case of humidity, water in gaseous form is homogeneously mixed with the air. As for every other substance, air has only a limited capacity to hold water. This limit is referred to as saturation. The difference between humid air and dry air is that they cannot be distinguished by the naked eye, i.e. they are both completely colorless and transparent. Above the saturation point, however, excess water (which condenses or precipitates out of the air as the air temperature drops below the saturation point) appears as the finest of water droplets in the form of fog or clouds. The amount of water condensing out of the air at saturation is dependent on the air temperature. The amount of moisture that can be held by the air increases exponentially with temperature. At 0 °C it is, for example, at 3.9 g/m³, and at 20 °C it already reaches 15 g/m³.

The most important relationships will be explained using an example:

A room contains air holding a certain amount of water vapor. If you now start to cool the air gradually, a certain temperature will be eventually reached where dew begins to appear on the walls or objects in the room. This temperature is referred to as the dew point. You can observe this process when air at room temperature is 20 °C is cooled at the window glass which is at 6 °C. The water vapor condensing from the air collects and runs down the window pane.

This makes it clear that the air is not uniformly capable of absorbing water vapor and that this capability is dependent on the air temperature. Thus, each air temperature at a specific air pressure is associated with a certain amount of water vapor that may not be exceeded without it forming dew.

![Fig. 2-19 The relationship between temperature and saturation humidity](image)

h,x-Diagram (or Psychrometric chart)

Fig. 2-19 shows the dependency of the largest possible water vapor amount which, depending on temperature, can be contained in a specified volume of air.

The variables relative and absolute humidity are used to provide a numerical representation of the amount of vapor contained in the air. The exact relationships are shown in the h,x diagram (psychrometric chart). They can be easily determined by measurements and made available with the help of graphs.

We now know what heat as well as the source of thermal radiation is and have received an idea of how difficult it is in practice to obtain exact temperature measurements. After that, we examined thermal expansion of materials and have seen, using practical examples, how this phenomenon can be constructively used and which processes it gives rise to in heating systems and heated rooms.

We have already seen how much energy is needed to heat or vaporize water, and know that air can only absorb a certain quantity of water vapor, and that this portion of water vapor is dependent on air temperature and pressure.
2.2.6. The enthalpy of substances

We have seen that the temperature of a substance corresponds to a certain oscillational condition or (level of excitement) of its atoms. If we wish to raise the temperature, we must stimulate the atoms more, and this requires energy. The energy quantity needed also depends on how many particles have to be excited, in other words, from the weight (mass) of the material.

The larger the mass, the greater the quantity of heat or enthalpy contained in the substance following the rise in temperature.

The quantity of heat contained in a substance is designated by $Q \text{ [kJ]}$.

**Specific heat**

The quantity of heat $Q$ can be calculated. But first we have to get to know a few variables. If we try to raise the temperature of 1 kg copper, 1 kg water and 1 kg air by 1 K, we would determine that we would need almost three times as much heat energy for air as for copper and for water eleven times as much.

The results are just as different for other materials. The quantity of heat necessary to raise the temperature thus does not depend only on mass, but also on the heat storage capacity of the material. We designate this as the **specific heat** $c$ of the material.

The specific heat capacity always refers to 1 kg of material weight and 1 K. Its unit is $[\text{J/kg} \cdot \text{K}]$. Thus, it states, how much J or kJ, respectively, are required to heat 1 kg of that material to 1 K.

The specific heat for copper, water and air are:

- **Copper**: $c = 381 \text{ [J/kg K]}$
- **Water**: $c = 4.190 \text{ [J/kg K]}$
- **Air**: $c = 1.004 \text{ [J/kg K]}$

The table shows the values for the specific heat of other materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>$c$ in kJ/kg K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>14.25</td>
</tr>
<tr>
<td>Helium</td>
<td>5.24</td>
</tr>
<tr>
<td><strong>Water</strong></td>
<td><strong>4.19</strong></td>
</tr>
<tr>
<td>Air</td>
<td>1.0</td>
</tr>
<tr>
<td>Steel</td>
<td>0.48</td>
</tr>
<tr>
<td>Copper</td>
<td>0.39</td>
</tr>
<tr>
<td>Oils</td>
<td>~ 2.00</td>
</tr>
</tbody>
</table>

Table 2-8 Specific heat of different materials

If we ignore hydrogen and helium, then water has the highest specific heat of all materials (including those not mentioned here). We thus need much more heat energy to bring water to a higher temperature than other substances. In exchange, however, we have correspondingly more heat energy with which we can operate stored in this quantity of water.

When making calculations involving the quantity of heat, we are thus interested in the weight (mass $m$), specific heat $c$ and the temperature difference $\Delta T \text{ (K)}$ before and after heating. The reason for this is that these determine, in a definitive manner, how much heat we have to add to the material. If we go in the other direction and place a heated body in a colder environment, then, from its mass, specific heat and the temperature drop between it and its environment, we can calculate the maximum quantity of heat this body can release.
**Quantity of heat Q**

The following formula is to be applied:

\[ Q = m \cdot c \cdot \Delta \theta \]

\[ Q = m \cdot c \cdot \Delta \theta \quad [\text{kg} \cdot \text{J/kg} \cdot \text{K}] = [\text{J}] \]

The unit of the quantity of heat is the Joule or 1,000 J = 1 kJ (kilojoule).

Thus, if we wish to raise the temperature of 200 kg of water in a heating system from 70 °C to 90 °C, we then need:

\[ Q = m \cdot c \cdot \Delta \theta = 200 \text{ kg} \cdot 4.19 \text{ kJ/kg} \cdot \text{K} \cdot 20 \text{ K} = 16,760 \text{ kJ} \]

If this water flows into the radiator at 70 °C and returns from there to the boiler at a temperature of 50 °C, then it has given up the 16,760 kJ acquired earlier. The heat is given up mostly as heat to the room, but some small part, referred to as heat loss, is given up through the piping to the environment (Fig. 2-20).

Fig. 2-20  Principle of a heating system

The example shows that we need 16,760 kJ in order to increase the temperature of 200 kg of water by 20 K. We have also seen that this heat energy is given up from the radiator to the air and as heat loss to the piping, so that the water returns to the boiler at 50 °C again. We have thus essentially sent a flow of heat to the radiator. This heat flow must be adjusted in winter to heating requirements. In other words, the boiler in this heating system has to generate the quantity of heat energy per hour that is used by the radiators, that is, the rooms.

**Heat output**

Energy (work) used in a specific time (h) is referred to as power.
The **thermal output** or heat flow \( Q \).

The required thermal output in our example is

\[ \dot{Q} = 16,760 \text{ kJ} / 3,600 \text{ s} \quad \dot{Q} = 4.66 \text{ kJ/s} = 4.66 \text{ kW} \]

The relationship between Joule and Watt is explained in the following paragraph.

In order to obtain a feeling for the magnitude of the heat content of different materials, we examine the heat energy supplied by common fuels next:
Material: | Enthalpy: | Thermal output / h: |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[kJ/kg]</td>
<td>[kJ/m³]</td>
</tr>
<tr>
<td>Fuel oil EL</td>
<td>42,000</td>
<td>35,500</td>
</tr>
<tr>
<td>Bituminous coal, coke</td>
<td>30,000</td>
<td></td>
</tr>
<tr>
<td>Town gas</td>
<td></td>
<td>16,000</td>
</tr>
<tr>
<td>Propane gas</td>
<td>46,000</td>
<td>93,000</td>
</tr>
<tr>
<td>Natural gas</td>
<td>39,000</td>
<td>34,000</td>
</tr>
</tbody>
</table>

Table 2-9 Approximate thermal energy of different combustibles

Accordingly, for our heating system, which heats using oil, the hourly consumption of fuel amounts to 4.66 kW / 11.6 kW/kg = 0.4 kg fuel oil.

### 2.2.6.1. Joule und Watt

The unity of Joules or Kilojoules is a basic unit of the SI system.

The first law of thermodynamics states: **Heat is energy.**

Only the form of energy is different when comparing thermal energy with mechanical energy; the quantity of energy can be specified in Joules in both cases.

Mechanical energy is often expressed in Nm (Newton-meters), electrical energy in Ws (Watt-seconds) and thermal energy in Joules.

The following applies: **1 Nm = 1 Ws = 1 J**

What exactly does the unit Joule stand for?

We know that the unit Joule stands for energy and

- **Energy** = force x distance
- **Force** = mass (kg) x acceleration (m/s²)
- **Distance** = Meter (m)

**Energy** = kg·m²/s² = Joule

The unit kg·m²/s² does not have anything to do with heat. How can we relate these mechanical units with a heat-related variable?

J.P. Joule, an English scientist (1818–1889), proved the relationship experimentally. He built the experimental apparatus shown in Fig. 2-21 and found the heat equivalent.

![Fig. 2-21 Joule’s experiment to determine the heat equivalent](image)
Through the movement of the rotor, the temperature of a given amount of water is raised by a given amount (interaction of the molecules increases their oscillation). This corresponds to supplying heat in kJ/kg.

Joule discovered that mass of $m = 1$ kg has to fall a distance of $h = 427$ m to create a quantity of heat equivalent to $Q = 4,188$ Joules.

This mass has a force ($G$) acting on it equal to the gravitational acceleration of the earth ($g$) times its mass ($m$). ($G = m \times g$).

For Joule’s experiment, this means:

**Energy = mass x acceleration x distance**

$$Q = m \cdot g \cdot h = 1\text{kg} \cdot 9.81\text{ m/s}^2 \cdot 427\text{ m} = 4.188 \text{ kg}\cdot\text{m}/\text{s}^2 = 4.188 \text{ Joule}$$

or:  
$$Q = 4.188 \text{ J} = 4,188 \text{ kJ}$$

**2.2.7. Heat transmission**

Wherever we perceive heat or observe thermal processes, we are involved with heat transmission processes. This means: heat transmission from solids to liquids, from liquids to gases and again to solids, etc.

The heat transmission chain in a hot water central heating system can, for example, appear as follows:

Gas burner flame $\Rightarrow$ boiler wall $\Rightarrow$ boiler water $\Rightarrow$ radiator $\Rightarrow$ air $\Rightarrow$ people, as well as walls, ceilings, floors, furniture $\Rightarrow$ outside air and earth.

**2.2.8. Heat conduction**

Heat conduction is the flow of heat through a material by means of particle-to-particle propagation of thermal excitation (Fig. 2-22).

![Fig. 2-22 Heat flowing through a material](image-url)
Heat transmission through heat conduction also takes place where two materials touch, e.g. from electric heating plate to cooking pot, from iron to the material being ironed, etc. (Fig. 2-23).

![Diagram of heat conduction](image)

**Coefficient of thermal conductivity**

We know of good and poor conductors. Heat conductivity is measured by the coefficient of thermal conductivity \( \lambda \) (lambda). It specifies the amount of heat energy transferred in one second between two parallel surfaces 1 m apart having a cross-section of 1 m\(^2\) with a temperature drop of 1 K.

The coefficient of thermal conductivity \( \lambda \) has the unit of \text{W/m K}.

![Coefficient of thermal conductivity \( \lambda \) of various materials](image)

The illustration shows that copper conducts heat approximately eight times better than iron, while air and porous “air-filled” materials such as cork, foam, our clothing, etc., conduct heat the least. These latter materials are also designated as **insulating materials**.

Heat conduction is thus the flow of heat into a material, or from material to material when the material particles come into close contact.

What happens, though, if heat should be transferred from a solid to a liquid or gaseous material, for example, from a wall to water or air? Isn’t there only minimal intimate contact here because the particles of the materials are continually flowing or moving in unordered fashion? Besides, doesn’t the heated air or heated water immediately flow from the heat source away and up? The heat transfer can thus not be as complete as when two solid bodies come into intimate contact.
And this is correct. For flowing media, such as water and air, the particles of the materials, because of their own movements, really only have brief contact with the solid material or, as we wish to say, with the wall. They can thus only accept heat through conduction during the short “contact” — some particles more and others less. The medium, water or air, is thus only “warmed up” and only in the area near the wall or heat source (Fig. 2-24). The material heated here expands, becoming lighter (reduced specific density) and moves upwards, taking its added heat with it. There is thus a heat flow. As they flow on, the particles exchange their captured heat with one another and with their colder environment. They also exchange heat with any wall they meet. Of course, the heat transfer here is also incomplete again because of the transient nature of the mutual contact of materials.

![Fig. 2-25 Heat conduction to walls]

Heat transfer from a wall to a flowing medium thus always creates a flow which carries heat that can again be retransferred to a solid wall.

2.2.9. Heat convection

“Taking heat, carrying heat and bringing heat” are designated as heat transfer through convection.

Convection

1. Carrying along energy or electrical charge by the smallest particles of a flow (physics).

2. Transporting air masses in a vertical direction.

Free and constrained flows

The unconstrained natural upward flow of the heated medium is referred to as free flow; guiding through pipes or air ducts is referred to as constrained flow.

The quantity of heat transferred per unit time by convection depends on the:

- temperature difference between the wall and the flowing medium,
- size of the wall surface,
- coefficients of thermal conductivity of the wall and the flowing medium, but mainly
- type and velocity of the flow; the larger the flow velocity, the larger the number of particles that come in contact with the wall and in doing so take up or release heat from it.

Heat transfer

Calculating the type, direction and velocity of flow is very difficult. Practitioners know that even the most careful of calculations only approximate the actual heat transfer from wall to medium or vice versa. Because of this, a characteristic value is used in practice. This value was established through frequent trials and is available in tables and diagrams. This characteristic value is referred to as the
Heat transfer coefficient $\alpha$ (alpha)
The value for alpha is always referenced to a surface area of 1 m$^2$ and specifies how many Watts are transferred from the medium to the wall or vice versa for a temperature difference of 1 K.
As an example, here are some alpha values for air and water:

**Heat transfer coefficient $\alpha$ in W/m$^2$·K:**
- Stationary air: 3 to 20
- Flowing air: 20 to 100
- Stationary water: 500 to 2,000
- Flowing water: 2,000 to 4,000

These few examples already indicate how strongly flowing velocity affects heat transfer, above all for air. For water, the effect of flow is not as strong because the water particles contact the wall more firmly than the transient air particles. From these values we can see why we can hold our hand for a long time in air flowing at 80 °C, but not in water at 80 °C: Heat transfer is approximately 20 times larger for water.

There are alpha-value tables and diagrams for all heat transfers occurring in practice, e.g. for water and air as a function of flow velocity at the heat transfer surfaces.

**Heat flow**
If you know the heat transfer coefficient ($\alpha$) for given flow conditions, you can calculate the heat flow $\Phi$ from the size of a given wall surface area ($A$) and the temperature difference ($\theta_W - \theta_M$) between the wall and medium:

$$\text{Heat flow } (\Phi) = \alpha \cdot A \cdot (\theta_W - \theta_M) \quad \text{[W/m}^2\cdot\text{K} \cdot \text{m}^2 \cdot \text{K}] = \text{[W]}$$

Fig. 2-26 Heat flow along a wall
In our field of work, we are often interested in the heat transfer from air or water to a temperature sensor, or how fast we can obtain a correctly measured result. In order to obtain good heat transfer, the installer of a ventilation system will, if possible, locate a rod-shaped temperature sensor at a position in the air duct where the flow velocity is especially large.

In practice, however, we are not only dealing with heat transfer processes where a wall restricts the flowing medium. We also are rather involved with processes where the wall separates two flowing media from one another, thus two gases with differing temperatures, two liquids or a gas and a liquid, for example:

- Hot combustion gas / boiler wall / boiler water
- Hot boiler water / radiator wall / room air
- Room air / house wall / outside air

**Heat throughput**

All these examples involve two heat transfer processes. We are interested in how much heat is transferred through the wall. As little heat as possible should pass through a house wall. On the other hand, as much heat as possible should pass through a boiler wall. This heat transfer, through a separating wall between two media and involving a dual heat transfer, is referred to as heat throughput.

We now know the factors that determine heat throughput. We recall what is involved here is not pure heat conduction because a prerequisite of that requires firm contact between the bodies, and firm bodily contacts for liquids or gases on this or that side of the wall do not exist.

Instead, the heat throughput is considerably influenced by both heat transfer coefficients, e.g.

- $\alpha_1$ room air/wall inner surface
- $\alpha_2$ wall outside surface/outside air,

i.e. two variables (wind, etc.), which are difficult to calculate

Heat throughput is additionally influenced by

- the surface area and thickness of the wall
- the heat conductivity of the wall or the different wall layers
  (e.g. interior finish, masonry, insulating material, exterior finish)
- the difference in temperature, e.g. between room and outside air.

When calculating heat throughput, we work with empirical values, i.e. values obtained from practical experiments and measurements, almost without exception. The characteristic value for heat throughput through a certain wall construction is the

**Overall coefficient of heat transfer** $U [\text{W/m}^2\cdot\text{K}]$.

Like the coefficient of heat transfer $\alpha$, it is based on a wall surface area of $1 \text{ m}^2$ and specifies how many Watts [W] pass through a wall when the temperature difference between the media on either side of the wall is $1 \text{ K}$.

The unit of the overall coefficient of heat transfer is thus the same as the heat transfer coefficient.
If you know the U-value of a wall, the calculation of the heat flow $\Phi$ through the wall (transmitted quantity of heat) is not difficult.

Fig. 2-27 shows the mathematical variables involved with the U-coefficient of a wall when the wall is made up of three layers of varying thickness $d$ and different coefficients of thermal conductivity $\lambda$.

$$\Phi = U \cdot A \cdot (\theta_1 - \theta_2)$$

Of course, house walls in no way always consist of only three layers, for example, of two brick layers and one insulation layer. Plaster is also there and possibly the inner wall is additionally covered with tiles or woodwork.

Further, there is a difference whether the masonry consists of customary bricks, clinker bricks, hollow bricks or a similar material. The thickness of the masonry varies with the purpose of the building. As a result, it is not surprising that tables of U-values of building materials can fill several pages in the building system handbooks.

<table>
<thead>
<tr>
<th>Some examples</th>
<th>U in W/m²·K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Window, single glazed</td>
<td>approx. 5</td>
</tr>
<tr>
<td>Window, double glazed</td>
<td>approx. 3</td>
</tr>
<tr>
<td>Double glazed window &amp; insulating glazing</td>
<td>approx. 1.5</td>
</tr>
<tr>
<td>Inner door</td>
<td>approx. 2.5</td>
</tr>
<tr>
<td>Outer door, wood</td>
<td>approx. 1.7</td>
</tr>
<tr>
<td>Brick wall, 24 cm thick</td>
<td>approx. 1.5</td>
</tr>
<tr>
<td>Brick wall, 36 cm thick</td>
<td>approx. 1</td>
</tr>
<tr>
<td>Concrete wall (nonporous), 250 mm</td>
<td>approx. 2.5</td>
</tr>
<tr>
<td>Sheet metal wall</td>
<td>approx. 6</td>
</tr>
</tbody>
</table>

Table 2-10 U-values of some window and wall constructions

When engineering a heating system, the heat flow through all the components of the enclosed surfaces of a house is calculated using the U-values. The heat flow, that is, the heat losses are then known. Also known is the required capacity of the heating system and the required heat emission of the radiators in the individual rooms. This allows being able to compensate for the heat losses even under extreme winter conditions. We will go into this subject in more depth later. Nevertheless, we can make a summary at this point:
Water and air are the media with which we will be predominantly dealing in HVAC systems. Heat transmission from a solid body or a wall to these media or vice versa takes place through convection, where we differentiate between heat transfer and heat throughput. The heat transfer coefficient $\alpha$ and the overall coefficient of heat transfer $U$ are the characterizing quantities for heat transmission from warmer to colder media. Using them allows calculating not only the heat losses through walls, windows, doors and piping, but also the required capacity of the heating system and radiators.

2.2.10. Thermal radiation

We have learned: Thermal radiation consists of long-wavelength electromagnetic oscillations that always exist when, through collisions of atoms, some of their electrons are temporarily thrown out of their normal orbits. Thermal radiation is a form of electromagnetic oscillation. As an electromagnetic radiation, thermal radiation, as does light, obeys optical laws, that is, it radiates in straight lines, is reflected and can easily pass through certain materials and negligibly penetrate others. Glass, for example, is essentially impervious to thermal radiation (Fig. 2-28).

Since it is electromagnetic energy, thermal radiation does not need any solid transmitting medium. On the contrary, it propagates essentially unimpeded through vacuums or air-filled rooms alike (e.g. radiation from the sun, light from light bulbs). When it strikes solid or liquid particles, it excites them thermally and, in doing so, loses energy itself. Simple gases such as oxygen ($\text{O}_2$), nitrogen ($\text{N}_2$) and hydrogen ($\text{H}_2$), dry air and all noble gases are diathermic, that is, transparent to thermal radiation. And gases that cannot absorb thermal radiation can also not radiate it. Gases and vapors consisting of molecules such as steam ($\text{H}_2\text{O}$), carbon monoxide ($\text{CO}$), carbon dioxide ($\text{CO}_2$), sulphur dioxide ($\text{SO}_2$), ammonia ($\text{NH}_3$), etc., absorb and emit radiation at certain wavelengths with differing intensities. The intensity of the radiation is a function of the gas temperature (e.g. flame of an oil or gas burner).

On the other hand, solids and liquids always emit thermal radiation, and the higher their temperature, the stronger the thermal radiation. Energy radiated by a material as thermal radiation increases with the fourth power of its absolute surface temperature. The intensity (power) of the emitted thermal radiation at a specific temperature is, however, not the same for all substances. It is dependent on the radiation constant $C$. For solid substances, this constant is strongly dependent on surface composition:
Radiation constant C

<table>
<thead>
<tr>
<th>Surface:</th>
<th>C in W/m²·K⁴</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black body</td>
<td>5.75·10⁻⁸</td>
</tr>
<tr>
<td>Highly polished metal</td>
<td>0.25·10⁻⁸</td>
</tr>
<tr>
<td>White, glossy enamel</td>
<td>5.20·10⁻⁸</td>
</tr>
<tr>
<td>Oil paints (all colors)</td>
<td>5.40·10⁻⁸</td>
</tr>
<tr>
<td>Aluminum paint (bronze paint)</td>
<td>2.20·10⁻⁸</td>
</tr>
<tr>
<td>Masonry, plastered</td>
<td>5.40·10⁻⁸</td>
</tr>
<tr>
<td>Water</td>
<td>5.40·10⁻⁸</td>
</tr>
</tbody>
</table>

Table 2-11: Approximate Radiation constant C of different types of surfaces

The table shows: An absolutely black body produces the most radiation. An identically sized, highly polished body of precious metal on the other hand, the least. The color does not play so large a roll. If we compare how much radiation a body emits relative to the amount an identically sized body absorbs, we will arrive at the same value.

Emission and absorption of thermal radiation are thus in balance: A material that emits small amounts of radiation also absorbs small amounts, and vice versa.

Calculating the heat energy transferred from one body to another by thermal radiation is nevertheless not so simple. This is because the angle of incidence of radiation must be taken into account as must the strength and frequency of the reflections as well as the fact that both bodies are simultaneously radiating and absorbing. As a result, we do not wish to get into the calculations, rather examine a couple of examples of heat transmission by radiation:

The glowing coils of an electric heater are strong heat radiators, especially since the directivity of the reflector is added in. The heat emission through convection is, however, negligible because the heat transmission surface (coils) is very small (Fig. 2-29).

If we blow on the glowing coils with a fan, they immediately cool because now the large number of air particles flowing past the coils removes the heat by convection (heat transfer in connection with forced flow). As a result, the thermal radiation immediately drops off: The thermal radiator has become an electric heat convector.
Certain heaters of a hot water central heating system are referred to as radiators because they give up a large portion of their heat into the room as radiation. If paneling is placed in front of the radiator, the radiation is blocked and the radiator functions as a convector only (Fig. 2-30).

In the case of convectors, we strive to bring the air into the closest possible contact with the heating surface. This achieves a high efficiency of heat emission by convection.

In ceiling radiant heating systems (left of Fig. 2-31) pipes are embedded in the ceiling or hung close to it. This provides a very large surface area, but the horizontal orientation of the "radiator" in the hottest area of the room provides for very little air movement. Heat emission takes place almost exclusively through radiation.

For the inverse orientation of floor heating systems (right of Fig. 2-31), the relationships are similar. Here, however, the portion of heat emission through convection is larger because the heated air can move upwards in contrast to ceiling heating where the heat, so to speak, "stays put" under the ceiling.

These examples show us that when there is heat transfer from one material to another, heat conduction; heat convection and thermal radiation almost always work together:

Heat is a form of energy that is difficult to master. Whenever we strive to heat a material on one end, some of the heat is lost on the other end through convection, radiation or heat conduction. Sometimes this is actually desired, but often it is nothing more than heat loss. And, taken literally, heating is nothing more than an ongoing compensation of heat losses.
2.2.11. Rule of mixture

Mixing temperature

The mixing law can be expressed as an equation for determining the mixing temperature $\theta_m$ that occurs when two liquids having masses $m_1$, $m_2$ with associated temperatures $\theta_1$, $\theta_2$ and specific thermal capacity $c_1$, $c_2$ are mixed together without adding or removing heat.

From the equilibrium of released and absorbed quantity of heat if follows:

$$Q_{up} = Q_{down}$$

$$m_1 \cdot c_1 \cdot (\theta_m - \theta_1) = m_2 \cdot c_2 \cdot (\theta_2 - \theta_m)$$

$$\theta_m = \frac{m_1 \cdot c_1 \cdot \theta_1 + m_2 \cdot c_2 \cdot \theta_2}{m_1 \cdot c_1 + m_2 \cdot c_2} \quad [\degree C]$$

or simplified for the mixing of two equal liquids $c_1 = c_2$:

$$\theta_m = \frac{m_1 \cdot \theta_1 + m_2 \cdot \theta_2}{m_1 + m_2} \quad [\degree C]$$

In HVAC engineering, mixing processes occur on the water-side for hydronic circuits (flow temperature control) and on the air-side for air mixing control (air damper control).

2.2.12. The time constant of heat transfer

Transmission behavior

In all heat transmission processes, the following question always crops up:

Which **quantity of heat** would be **transmitted per unit time** from a wall to a gas or to a liquid or from these to a wall for a given **temperature difference** of $x$ Kelvin?

We have learned that the quantity of heat transmitted is dependent on certain characteristics of the wall, namely the coefficient of heat transfer $\alpha$ or the overall coefficient of heat transfer $k$. Thus in a specific case, that is, for a wall of given size and material, the quantity of heat transmitted per unit time is only a function of the temperature difference. But this temperature difference becomes smaller as the heat transfer process continues. Thus, the quantity of heat transmitted becomes smaller and smaller. If, for example, a cold metal cube is placed on a hot plate preheated to 100 °C, the temperature of the cube initially increases rapidly because the temperature difference is relatively large. Towards the end of the heat transmission period, however, the cube temperature increases only slightly during the same amount of time because the temperature difference is perhaps only 1 K and correspondingly less heat is transmitted. The quantity of heat transmitted per unit time decreases continuously.
Exponential function

Processes in which there are changes in the magnitude of the magnitude itself are known as exponential functions, or simply e-functions. In Fig. 2-32, we clearly see how the change in temperature per unit time decreases continuously because the temperature difference which has to be overcome also decreases continuously (and this is the factor determining the quantity of heat transmitted!).

Nearly 2/3 (mathematically exact: 0.632 or 63.2%) of the total temperature difference $\Delta \theta_{\text{max}}$ – here designated as $\Delta x = 100 \%$ – is overcome in time $T_1$ (referred to as the time constant).

During the next identical unit of time $T_2$, once again 63.2% of the remaining 36.8% is overcome.

And exactly the same change occurs in the third unit of time $T_3$: Again, 63.2% of the remaining temperature difference is overcome, etc., until at approximately 5 $T$, the balance is essentially reached.

A specific example:

We immerse a thermometer into melting ice until it indicates 0 °C. Then, we remove it and immediately immerse it in water which is held at a constant 100 °C. At the same time, we start a stop watch and measure how long it takes the thermometer to reach 63 °C. Let’s assume that for our experimental conditions, this takes 20 seconds. Now, we can predict that after an additional 20 seconds, the thermometer would show 86 °C and after another 20 seconds, 95 °C. Afterwards, the temperature would increase only very slowly. Only after about five times 20 seconds, would it finally show almost 100 °C. Theoretically, that is, mathematically speaking, 100 °C would be attained only after an infinite period of time.
2.3. Hydrodynamics (fluid mechanics)

Flow
Flow is the coherent movement of fluids, gases and plasmas occurring in a continual manner. We differentiate between:
- laminar flow
- turbulent flow

Fiction-free flow
If we neglect the friction occurring between individual liquid layers at the border surfaces of bodies and liquids, we then speak of friction-free or ideal flow. While friction-free flow has importance for the general understanding of flow processes and for calculating speed and pressure relationships (e.g. of a turbine blade or an airplane wing), it is not relevant for HVAC systems.

Frictional flow
The flow of a liquid or gas in a pipe can be laminar (layered) or turbulent (whirling). In laminar flow, the individual (liquid) particles move along parallel flow lines generally with different velocities \( w \). There is friction between the individual shear thread (friction); the more viscous the fluid, the greater the friction.

2.3.1. Laminar flow

A flow with non-crossing path lines is called laminar flow. The liquid particles slip as in layers over one another and produce a parabolic velocity profile. Shear stresses arise with an associated frictional resistance. Laminar flow is not suited for heat transmission from fluids. It is nevertheless used for fast acting displacement ventilation in ventilation installation practice (in specific plant situation such as clean rooms, operating areas, ...).

![Velocity profile for laminar flow in a pipe](image)

2.3.2. Turbulent flow

Turbulent flow occurs when there are turbulent, whirling flow patterns. The current threads decay and become lost. Crossing and mixing movements occur. The center parts transfer energy to the outer layers. The slower outer particles move inward causing a braking effect, flattening the velocity profile.

![Velocity profile for turbulent slow](image)

HVAC applications deal almost exclusively with turbulent flow. Angled air ducts, ventilation equipment such as air heating coils, fans, etc., and projecting edges swirl the flow. The definitive flow profile in a pipe only occurs following a certain distance whose length corresponds to approximately 10 times the diameter of the pipe under consideration.
Reynolds number
For a given pipe, the transition from laminar to turbulent flow occurs at a specific critical velocity defined by the critical velocity, the so-called critical Reynolds number (Re) (Re= numeric value calculated from pipe diameter, flow rate and viscosity of a liquid). It is influenced by wall friction, velocity changes and other factors.

Flow resistance
Flow resistance in pipes, ducts and elbow pipes is also dependent on material composition (piping or duct walls). In order to transport a liquid or gas through a pipe, a pressure differential Δp must be applied to overcome frictional resistance. To keep the pressure drop as small as possible, deflectors are built into the air ducts or the piping is designed accordingly.

The drag coefficient $\zeta$ (zeta), multiplied with the dynamic pressure $p_{dyn}$ in the inflow cross section equals the pressure loss $\Delta p$ in the duct pipe fitting in question:

$$\Delta p = \zeta \cdot p \cdot \frac{w^2}{2} \text{[Pa]}$$

Fig. 2-35 Decreasing $\Delta p$ by using different shapes of pipes or ducts and installing deflectors

A square duct has sides the length of 10 cm and laminar flow at the entry. The flow pattern 20 cm after a 90° bend displays a strongly distorted velocity profile. Reverse currents can even occur. After approximately 80 cm, the velocity profile is again symmetrical. If no further disturbances occur, the previous flow profile is only again reached after approximately 7 to 8 m.

These processes, of course, have to be taken into account when making measurements in piping or ducting networks.
2.3.3. Velocity and pressure

The average velocity determined from a velocity profile multiplied by the cross-section yields a volume flow; if you measure the velocity with a velocity sensor, then you obtain the associated velocity profile.

**Continuity equation**

From the rule of conservation of mass the following applies for an incompressible liquid flowing in a pipe:

\[ A_1 \cdot w_1 = A_2 \cdot w_2 \]

- \( A_{1,2} \) = cross sectional area [m²]
- \( w_{1,2} \) = velocity [m/s]

**The energy rule**

Continuity equation: The same mass flows through each cross-section of a pipe per unit time. For incompressible media, the same volume applies.

If a small volume of liquid flows with volume \( v \) and mass \( m \) without any height change through a horizontally narrowing pipe, the velocity increases at the narrowest point from \( w_1 \) to \( w_2 \) and thus the dynamic pressure from \( p_{dyn1} \) to \( p_{dyn2} \) (Fig. 2-37a). The static pressure also changes correspondingly because the velocity changes in accordance with the new cross-section (Fig. 2-37b).

According to Bernoulli, the sum of the static pressure and the dynamic pressure is constant at all locations in the pipe for loss free flows.

\[ p_{tot} = p_{stat} + p_{dyn} = \text{constant} \]

- \( p_{stat} \) = static pressure (surface pressure) in Pa
- \( p_{dyn} = \rho/2 \cdot w^2 \) = dynamic pressure in Pa
- \( p_{tot} = p_{stat} + \rho/2 \cdot w^2 \) = total pressure in Pa with \( \rho \) (density) = m/V
This means that velocity energy can be converted into pressure energy, and vice versa. In practice, these processes are of course subject to losses. These losses \( (\Delta p_v) \) accumulate from the frictional resistance \( R \) (\( R \) = pressure drop per m pipe) multiplied by the piping length in meters plus the individual resistances derived from \( \zeta \cdot p_{dyn} \). If a medium with pressure drop \( (\Delta p_v) \) flows through a horizontal piece of pipe from point 1 to point 2, the total pressure at point 2 is given by:

\[
P_{tot2} = p_{tot1} - \Delta p_v
\]

You can determine the velocity and thus the amount flowing due to the pressure differential.

![Fig. 2-38 Measuring pressure with a Pitot tube](image)

The fluid column \( p_{dyn} \) can be provided with a velocity scale because \( p_{dyn} = \rho/2 \cdot w^2 \).

Velocity is thus *indirectly* determined via Pitot tube.

Pressure losses due to friction occur in ventilation systems with their obstacles, bends, etc. These must be overcome by the fan by increasing the static pressure. Fig. 2-39 shows the typical pressure variation for such a system.

The static and total pressure both decrease upstream of the fan because of suction. The highest values for these variables are reached just downstream of the fan. Heat transfer units account for considerable pressure losses, as do 90°-bends, but less so in the duct sections between bends. The initial pressure \( p_o \) is again reached in the room following air discharge.

![Fig. 2-39 Pressure profile in a ventilation system](image)
2.4. Hygienic fundamentals

2.4.1. Heat balance of the human body

A person's body temperature is approximately 37 °C. However, the average skin temperature is 33 °C. People generate heat by chemical "combustion" (oxidation) of foods. This is, in principle, energy from the sun needed to grow food in the form of plants that is again being released. At a 33 °C skin surface temperature, the body temperature of people in and around Europe is higher than the temperature of the environment almost throughout the year. People thus release heat continuously approximately as follows:

- 35 % through heat conduction and convection
- 35 % through thermal radiation
- 24 % through water vapor (sweating, breathing)
- 6 % to heat ingested food, drinks and inhaled air (Fig. 2-40).

Fig. 2-40 Percentage heat release of a human body

The percentages given above are averages. In summer or during intensive activity, the heat is released more through evaporation; in winter, more by convection and radiation.

However, in whichever form the heat is transferred, the body always strives to maintain its normal temperature, since it is only at this temperature that life functions can be carried out normally. In winter, therefore, the body reduces its heat transfer by contracting the skin: Heated blood can no longer reach the outer capillaries. On the other hand, in summer or in heated rooms, these capillaries expand, so that more heat can be transferred through evaporation. There are limits to this natural temperature control, however.
Continuous contraction of the blood vessels can lead to frostbite, while continuous expansion can lead to an extreme drop in blood pressure (heat stroke). The humans supplement this automatic temperature control mechanism by wearing suitable clothes, by adjusting food intake and by heating or cooling the rooms they inhabit.

The total amount of heat given off by a body is not only a function of the temperature of its surroundings, but even more of its momentary physical activity (Fig. 2-41).

These heat quantities become interesting when designing heating, ventilation or air conditioning systems mainly for rooms frequently occupied by large numbers of persons (e.g. department stores, office buildings, school buildings, movie theatres, restaurants, cinema, etc.).

**Interior heat gains**

Because of the good insulation of buildings and the thick building walls, the heat increase caused by interior heat sources, such as lamps, computers, copying machines, etc., is often so large in peak periods that department stores must even be cooled in winter. The resulting heat is referred to as **interior heat gains**.

This example shows that a comfortable heating and ventilation system must not only be configured for the normal case, but that even in the design phase the maximum and minimum personnel loading conditions must be taken into account. In winter, the interior heat gain can be recovered as a heat contribution, thus reducing energy consumption. In summer, on the other hand, the heat gain has to be "cooled away" using considerable energy.

In a medium-sized movie theatre, 300 people produce about 30 kW which, for a three-hour showing, amounts to a thermal output of approximately 90 kWh.

People do not become conscious of the ongoing heat release from their bodies as long as their bodies have no trouble maintaining a heat balance with the surroundings. Only when this limit is exceeded and persons begin to shiver or perspire, that is, when they feel uncomfortable, only then do they notice that they have "a temperature" and also notice that, due to this temperature, they have an ongoing heat exchange with their surroundings.

The goal of HVAC technology is thus to treat the rooms which people occupy in such a manner that their bodies can effortlessly maintain a temperature balance with the room environment. This task is certainly not an easy one because the feeling of comfort for each person is as different as each person’s personality.

### 2.4.2. Comfortable room temperature

From a thermal point of view, people are bodies with a surface temperature of approximately 33 °C. If people are inside a room, be it a living room, working room or recreation room of some sort or another, they are – with this 33 °C surface temperature – in a constant heat exchange process with the ceiling, the floor, the windows, the radiators, even with the furniture and lamps, in short, with their environment (Fig. 2-42). If the temperature of the environment is too low, the people give up too much heat. They shiver and feel cold and uncomfortable (left half of figure).
If the temperature of the surroundings is too high, then bodily heat cannot be given up fast enough. People begin to sweat and also feel uncomfortable in this situation (right half of figure).

So what is the proper temperature, the really comfortable room temperature, a temperature where we neither shiver nor perspire? And what other criteria also play an important role?

The comfortable room temperature initially depends on how active the people are, because we know, the larger the bodily effort, the bigger the heat production. And the body must be able to give off this heat if people are to feel comfortable. Additional criteria for determining a comfortable room temperature are:

- personal temperament
- eating habits
- clothing habits

In living rooms, offices and other working and recreation rooms in which only light jobs are carried out, the comfortable temperature lies somewhere between 20 and 22 °C, provided that the room is part of a well-insulated house.

On the other hand, in a cellar having cold and damp walls, one would certainly be uncomfortable even at 22 °C. Why? The explanation lies with how a person gives up bodily heat:

- approx. 35 % through heat conduction and convection
- approx. 35 % through thermal radiation
- approx. 30 % through evaporation, etc.

A room temperature of 22 °C represents a harmonic “counterbalance” for the 35 % heat transfer by conduction and convection, as well as for the 30 % heat transfer by evaporation. The 35 % heat transfer by thermal radiation cannot be included in this because it is absorbed by the cold and humid cellar walls having a perhaps only 12 °C temperature. Because of this enormous heat loss we no longer sense the room temperature to be 22 °C, but rather at perhaps only 15 °C, and thus the uncomfortable feeling.

On the other hand, with a wall temperature of for example 17 °C we sense an actual room temperature of 22 °C to be approximately 18…19 °C and hence, generally as comfortable. Due to the influence of radiation, we must always differentiate between measured temperature and room temperature actually felt.

The mutual influence of the radiation is illustrated in Fig. 2-43 by waves of radiation having differing wavelengths. On the left, the heat loss by radiation is uncompensated because the cold wall emits too little thermal radiation. Hence a room temperature of 22 °C is felt to be only approximately 15 °C.
On the right, on the other hand, the person and wall are essentially in balance with respect to the radiation.

![Fig. 2-43 Influence of radiation on comfort](image)

In all poorly or inadequately insulated houses, we feel drafts coming from the walls. Because we give off a greater amount of heat by radiation to these cold walls, we constantly have the feeling “that there is a cold dart flowing past the neck.”

The only way out of this situation is to raise the room temperature so that the temperature sensed is about 20 °C even though the effective temperature may lie between 22 and 23 °C. The graph (Fig. ) illustrates these temperature relationships. Left is the wall temperature, on the x-axis, the room air temperature is shown.

![Fig. 2-44 Graph for determining the room temperature needed to compensate for the wall temperature in order to provide control](image)

If the intersection point of the two temperature values lies within the hatched area, the room temperature is generally found to be comfortable. It goes without saying that this graph is valid only for living rooms, offices and working rooms in which no heavy physical work is carried out.

Windows are also cold surfaces which are correspondingly detrimental to comfort. Double glazed or insulated windows can reduce these disturbances.

In addition, radiators are always mounted under windows. This way they not only create a warm curtain in front of the windows, but due to their thermal radiation also compensate almost fully for the increased thermal radiation of persons to the cold window surfaces. Fig. 2-45 illustrates the mutual radiation exchange for various heat sources.

Excess thermal radiation from excessively hot radiators is uncomfortable because then people cannot give off their own share of radiation unhindered: On the contrary, they “heat up” even more.
Comfort also plays a role for radiation ceiling heating in rooms less than 2.50 m high. Here, a ceiling temperature of 32 °C must not be exceeded. In the case of floor heating, the maximum allowable surface temperature in those areas that are frequented often is 25...26 °C.

A chilled ceiling against this would be perceived as pleasant because body heat can now radiate (a cool head and warm feet are always desirable).

These comfort temperatures should be considered as average values for living, working and other rooms in which light physical work is carried out, e.g. in offices and sales rooms, laboratories, etc. The temperature in rooms where heavy physical work is performed must be considerably lower, so that the body can give off heat without perspiring, if possible.

Thus, there is no fixed value for a comfortable temperature because there are many other factors and influences which determine the comfort level:

**Humidity**
If the air is too dry, the mucous membranes are irritated by dust particles in the air much more than they would be if the humidity were normal. On the other hand, we sense excessively humid air to be “muggy” because we cannot give off unhindered the perspiration share of our total heat transfer.

**Air movement**
Too rapid a movement of air at normal temperature increases the amount of heat transfer by evaporation or convection and this is sensed as cold or drafty.

**Air purity**
Smoke, dust and stale air cause discomfort (nausea).

**Oxygen content**
If the oxygen content of the air is too low, the carbon dioxide (CO₂) level becomes too high. This can occur in overfilled, generally also overheated rooms and can produce conditions ranging from drowsiness to nausea and fainting.

**Degree of ionization**
The electric charge in the air, especially before and after thunderstorms and "Foehn" winds (warm winds blowing over mountains), etc., strongly influence the feeling of comfort (nervousness, irritation, blood circulation complaints).
In addition to temperature control, all the above mentioned factors must be taken into account in ventilation and air conditioning systems. Additionally, the color and size of the rooms, their furniture, carpets, illumination, etc., play an important role with respect to comfort because these elements are also sensed as "hot" or "cold," making a stay in these rooms a comfortable or uncomfortable experience. Thus, we see that each of us has our own, fully individual sense of comfort so that rooms used collectively can only be designed for average comfort.

Hence we see: The comfortable room temperature does not really exist. But with regard to living (and working) comfort we note:

What is important is not the set and measured temperatures, but the sensed room temperature

In Bauten mit schlecht isolierten und daher kalten Außenwänden wird die Raumtemperatur stets als kühler empfunden als sie effektiv ist, da der Körper hier übermäßig viel Wärme verliert. Abhilfe schafft nur eine etwas höhere Raumtemperatur. Dies gilt auch für noch nicht ausgetrocknete Neubauten.

Due to all these reasons, a room temperature controller should always be set only according to the feeling of comfort, whereby the "usual" standard values should only be used as guide values to facilitate the initial setting
3 Heating plant

3.1. Simple heating plants

The demands of a user of a building for comfortable room temperatures also in cold weather are ensured with heating plants. It can be roughly divided into the following sections:

- Heat generation
- Heat distribution
- Heat consumption (emission to the room)

The heat plant also provides heat for domestic hot water as well as for the kitchen and bathroom.

---

3.2. Dividing the heating systems

Heating systems can be subdivided according to various criterias:

- System temperatures
- Heat carrier
- Heat generator
- Heating surface
- Pipe system
- Distribution system

The following division demonstrates a possible compilation. The division itself differs from country to country and is based on the respective norms and standards.
3.3. Heat generation in water heaters

3.3.1. Oil and gas boilers

3.3.1.1. Overview

Boilers for oil and gas firing can be divided by different criterias, for example:

- Boiler material:
  - Cast-iron boiler
  - Steel boiler
  - Hybrid boiler (combustion chamber made of cast iron, boiler body made out of steel)

- Type:
  - Stand-alone boiler
  - Wall boiler

- Operating principle:
  - Condensing boiler
  - Low-temperature boiler
  - Constant temperature boiler

- Exhaust systems:
  - Three-pass principle
  - Two-pass principle

3.3.1.2. Boiler materials and types

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Cast iron</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance grading</td>
<td>Good performance grading because of the design with its links</td>
<td>Wide range of performance grading within a product family</td>
</tr>
<tr>
<td>Weight</td>
<td>Insignificantly heavier than steel</td>
<td>Lighter than cast iron</td>
</tr>
<tr>
<td>Corrosion resistance</td>
<td>More resistant to corrosion than steel</td>
<td>Not resistant against corrosion</td>
</tr>
<tr>
<td>Assembling (of large boilers)</td>
<td>Links can be brought separately and then assembled</td>
<td>Assembly through welding on site only</td>
</tr>
</tbody>
</table>
The area in condensing boilers, in which the water vapor content from the exhaust gas is condensing, is mostly made out of corrosion-resistant, high-alloyed steel. Boilers can be made for either standing or mounting on a wall.

![Condensing boilers comparison](source: Viessmann)

### 3.3.1.3. Mode of operation for boilers

**Condensing boilers**

The condensing boiler is currently the most efficient type of boiler. The condensing boiler works with system temperatures, which are adjusted according to outdoor conditions. Furthermore, the condensation is explicitly permitted by means of cooling the exhaust gases and thus systematically using the condensation heat. By using the latter, the efficiency of the boiler can be increased significantly. The rate of efficiency amounts to about 95% (related to the higher heating value). Nowadays, in almost every country condensing boilers must by law be installed in new buildings.

**Comparison between higher heating value and lower heating value**

At combustion, the oxygen from the combustion air reacts with the hydrogen from the fuel, whereby the exhaust gas gets loaded with water vapor. If these exhaust gases, however, are merely discharged, the latent heat of the water vapor in the exhaust gases is lost. The condensing boiler technology utilizes the additional energy existing in the exhaust gas. The lower and higher heating values indicate how much thermal energy the relevant fuel can release at combustion.

- The lower heating value describes the thermal energy, which is released when the fuel is simply burned and the water vapor in the exhaust fumes is not condensed and used. The lower heating value is lower than the higher heating value.
- The higher heating value describes the thermal energy, which can be supplied by burning the fuel and the additional use of the heat gained from condensing the water vapor of the exhaust fumes. The higher heating value is higher than the lower heating value, because it includes the directly usable thermal energy as well as the latent heat of the water vapor in the exhaust gases. With the efficiency rate based on the lower heating value, this then leads to a rate of efficiency above 100 %, which is technically impossible, but sounds promising.

**Operating principle of condensing boiler**

The condensing boiler is the most efficient if the heating plant works with low return temperature, because the water flowing back out of the heating plant is first lead through a heat exchanger in the exhaust gas area. Thereby, the water vapor in the exhaust gas is condensed (condensation point for oil EL ca. 47 °C, condensation point for natural gas ca. 57 °C) and the greater evaporation heat contained in the water vapor is used. Thus, the return water is preheated and arrives with a higher temperature in the second heat exchanger located in the actual combustion chamber. The condensation area must be made of a corrosion-resistant material, because the exhaust gas contains acidic substances (e.g.: sulfur, chlorine) in small quantities, and these acidic substances then enter the condensed water in the condensing process. The acidic condensed water is then neutralized by means of a pellet made from calcium and magnesium oxide and reacts with salt and water, which is allowed to be supplied into the drainage.
Constant temperature boiler

Nowadays, the constant temperature boiler is normally not installed anymore. It is still seen in existing plants, though. The peculiarity of this type is the operation with constantly high system temperatures of 70 °C to 90 °C. This was meant to keep the water vapor of the exhaust gases from condensing. This boiler has very high exhaust temperatures and great heat losses due to the constant heating. As it constantly upholds the same water temperature, it can’t adjust the exhaust gas temperatures to the outside temperature conditions. The heat losses of this boiler amount to 20%. The rate of efficiency of a boiler such as this (concerning the higher heating value) amount to as little as 70%.

Low-temperature boiler

The low-temperature boiler is an advancement from the constant temperature boiler. It has low system temperatures and can adjust them flexibly. Its water temperatures are in the range of 35 °C to 70 °C. Depending on the selected system temperature, condensation of exhaust gases can take place in the low-temperature boiler. This is not intentionally so – unlike in the condensing boiler. It can modulate its water temperature based on outdoor temperature. Its rate of efficiency is considerably higher as the one of the constant temperature boiler, as significantly lower losses occur. Installing this boiler has become uncommon in many countries.

3.3.1.4. Exhaust system

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Three-pass principle</th>
<th>Two-pass principle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flame temperature</td>
<td>Low flame temperature 1,000°C to 1,200°C</td>
<td>High flame temperature &gt; 1,400°C</td>
</tr>
<tr>
<td>Retention time of exhaust gases in combustion zone</td>
<td>The exhaust gases are directly discharged and thus have a short retention time.</td>
<td>The exhaust gases are lead back and thus have a long retention time.</td>
</tr>
<tr>
<td>Nitric oxide (NOx) production</td>
<td>The low flame temperature and short retention time leads to a smaller nitric oxide production.</td>
<td>The high flame temperature and long retention time leads to a high nitric oxide production.</td>
</tr>
</tbody>
</table>

Table 3-1 Exhaust system
Nitric oxide production

Nitric oxide (NO\textsubscript{x}) is a chemical compound composed of nitrogen and oxygen. If it reacts with water vapor, nitric acid is formed. The latter is considered to be the cause of acidification of soil and the resulting consequences of hard water and forest dieback (also: Waldsterben). This nitric acid also emerges during the combustion of oil or gas. It emerges, when the exhaust gases are exposed to high temperatures and have a long retention time in these temperatures. Measurements to prevent the forming of this nitric acid are to cool the flames and a shorter retention time. The low NO\textsubscript{x} burner makes it possible to cool flames. This type of burner leads exhaust gases back to the burner and mixes it with the burner flame. Thus, the flame temperature is lowered. The exhaust system according to the three-pass principle ensures that the exhaust gas is lead out of the combustion chamber and thus the retention time is shorter.

3.3.1.5. Oil burner

Atomizing oil burner

The atomizing burner is the most used burner type. The heating oil is transported out of the oil tank via oil pump. First, the heating oil filter ensures that no suspended solids are in the oil, which could later clog the oil nozzle. Then, the heating oil is preheated to lower its viscosity and make it easier to atomize the oil. After that, the oil goes on to the oil nozzle, where it is atomized as thoroughly as possible, swirled and mixed with air. The air for the combustion is lead into the oil nuzzle via the blower fan. Next, this mixture of oil and air is combusted.

Blue flame burner

The blue flame burner is an atomizing oil burner that produces less nitric oxide. Hot flame gases are lead back via the openings in the mixing tube of the blue flame burner. These flame gases ensure that the oil almost completely evaporates. Thus, the oil is completely combusted. This reduces the soot generation as well as the nitric oxide emission.

Fig. 3-6 Operating principle of a blue flame burner (left) and display of a blue flame burner (right) (source: SBZ)
Vaporizing oil burner
This burner type creates oil vapor by heating the incoming heating oil at the beginning via filament wire. The blower fan supplies the air to the oil vapor and thus fuses it to a mixture of oil vapor and air. This mixture then combusts atmospherically in the combustion chamber. Once the burner is ignited, the heat radiation of the flame itself is sufficient to vaporize the rest of the oil.

3.3.1.6. Gas burners
Forced-air burner
The forced-air burner is almost identical to the vaporizing burner concerning function and structure. Here, too, the gas is first mixed with the combustion air and subsequently combusted. The combustible gas flows via gas control pipe into the burner. This gas control pipe mostly has a shut-off valve and gas filter. The forced-air burner also has a gas pressure controller, which balances the pressure fluctuations in the gas grid. The most important element is the solenoid valve, which immediately shuts off the gas flow and disconnects the burner from the remaining gas grid in case of malfunction or full shutdown of the burner. Flame gases are also recycled in this type of burner. The former makes sure that the flame temperature and production of nitric oxide are kept down. On the one hand, the forced-air burner has a higher rate of efficiency compared to the atmospheric burner. On the other hand, this type of burner is noisier and consumes more electrical energy for the blower fan.

Atmospheric burner
In the atmospheric burner, the combustion air flows through the thermal buoyancy of the exhaust gases and the consequent negative pressure back into the mixing tube. The combustion air is mixed with the gas in the mixing tube. The premixture makes sure that more oxygen is available than the combustion itself actually requires. This leads to a lower flame temperature and nitric oxide production. The mixture is combusted in the openings of the mixing tube.

Matrix radiant burner
The operating principle of the matrix radiant burner is essentially the same as the one of the atmospheric burner. The gas-air-mixture is not burned in a tube, though, but at a hemispherical stainless steel mesh and the combustion air is added via fan. Thereby, the mesh is heated up and gives off heat almost exclusively in form of radiation. The flame temperature and the here to connected nitric oxide production are therefore even lower.

Fig. 3-7 Forced air burner (right) (source: Weishaupt) and matrix radiant burner (left) (source: Viessmann)
3.3.2. Wood boiler

3.3.2.1. Materials
Wood boilers are also made of either cast iron or steel. The components, which are exposed to high temperatures, such as the combustion chamber, are made from ceramics, respectively fire clay (grogg, chamotte), cast-iron or steel.

3.3.2.2. Storage and provision of fuels

Wood logs
Wood logs have to be dried before they can be burned. They should have only 15 – 20% residual moisture, which is reached after 1 to 2 years of storing. The storage space for the wood logs should have good ventilation, be protected from rain and be as sunny as possible so that the wood logs can dry fast. They should also be chopped before storing to speed up the drying process.

Wood chippings
Wood chippings are added to the boiler via auger conveyor. The rotating spiral winding transports the wood chippings mechanically into the boiler. The wood chipping storage should be located in immediate proximity to the heating center, so that the auger conveyor is efficient.

Pellets
If the consumption is low, then pellets can be bought in bags and added manually to the boiler itself if necessary. Otherwise, the pellets are normally delivered by tank truck and blown into the storage room. The storage room can either be a separate room, a textile silo or an underground tank, whereby the transportation of the pellets to the boiler happens automatically with either storage system. The transportation can either be done via auger conveyor where the storage room has to be located directly next to the heating center or via suction system. Here, the pellets can be transported over distances of up to 25 m.
3.3.2.3. Combustion system

**Boiler with lower combustion system and lower vent**
Here only the bottom layer of the fuel burns. Thus, the boiler settings are constant and easier to control. The rate of efficiency is significantly higher than the ones of boilers with an upper combustion system. Due to the longer exhaust gas path, more heat can be transferred.
All wood boilers with various types of fuels are presently constructed with this system.

**Boiler with upper combustion system and upper vent**
All of the fuel burns during the combustion. The heat output fluctuates according to how much of the fuel is left over. High outputs at short duration can be achieved. The performance is reduced after refilling.

**Boiler with upper combustion and lower vent**
The combustion system is the same as with the upper combustion. Additional heat can be transferred to the heating water because of the longer exhaust gas path.

**Burn-through**
The burn-through is similar to the principle of the upper combustion system. The only difference is that the combustion air flows above a grate to get to the fuel and because of that, all of the fuel burns. Fireplace stoves often use this principle.
3.3.2.4. Wood boiler

Wood boilers are manually filled with roughly cut wood pieces (logs). The wood pieces are layered on top of each other on a slab made of fire clay. Wood boilers mostly work with a lower combustion system. First, the wood pieces are dried repeatedly. After the pyrolysis of the wood and the precombustion of the highly flammable components, the main combustion takes place. The output control of the wood boiler is done via the supplied combustion air volume. The latter is employed by means of the air valve, which is powered by an actuator. Modern boilers possess a step less, speed-controlled blow fan. The combustion air supply is adjusted according to measured exhaust gas temperatures and residual oxygen content (oxygen sensor) in the exhaust gas itself. Consequently, the pollutant emissions are lowered and the rate of efficiency is raised. The rate of efficiency lies at > 90%. The complete combustion of an entire filling lasts 4 to 6 hours.

![Wood boiler with lower combustion system (source: Guntamatic)](image)

Fig. 3-12 Wood boiler with lower combustion system (source: Guntamatic)

1. Filling door with suction duct
2. Filling room with protective lining
3. Cast grate
4. Ash drawer
5. Primary and secondary air damper motor
6. Primary air
7. Secondary air
8. High-temperature combustion chamber
9. Cleaning lid
10. Tubular heat exchanger
11. Dust collecting zone
12. Cleaning tube (front)
13. speed-controlled blower
14. Oxygen sensor
15. Operating unit/controller
16. Cleaning lever

3.3.2.5. Pellets boiler

The pellets boiler often contains a separate, internal storage unit. This storage unit can either be filled with pellets directly from a bag or via suction or auger conveyor system directly connected to an external storage chamber. The pellets are transported out of the storage chamber into the combustion chamber by means of a dosing screw. The ignition in the pellets boiler happens via hot-air blower. The pellets then burn on the burner pot. The control of combustion air and fuel volume supply acts as output control. The probe forwards the relevant data for low-emission combustion to the exhaust pipe, which measures the temperature and the residual oxygen content (oxygen sensor) in the exhaust gas.
3.3.2.6. Wood chip boiler

The fuel is loosened in the storage chamber in a first step. Then, it is transported to the boiler by means of the auger conveyer system. The wood chippings can either be directly fed into the boiler or be brought into a pre-boiler before that, depending on the type of plant. If the plant has a pre-boiler, the fuel is gassed before it is burned in the boiler. The combustion is similar to the combustion in the pellets boiler. The procedures of output control by controlling of the combustion air and of fuel supply are identical.

Wood chip boilers are mainly used in larger plants, which for example supply several residential houses or even whole neighborhoods.
3.3.3. Thermal solar plant

The sun constantly supplies a great amount of energy to the earth. This is mostly done by means of thermal radiation. The sun annually supplies the earth with 5000 times the energy the human race needs (heat, electric power, traffic). This chapter covers the active use of solar heat in radiators and for the production of domestic hot water.

3.3.3.1. Global radiation and its composition

The rate of energy of solar radiation outside of earth’s atmosphere amounts to about 1350 W/m². This figure is also called “solar constant”. The solar radiation is minimized on its way through earth’s atmosphere because of reflection and absorption and thus only a fraction reaches the earth’s surface. This fraction is also called “global radiation” and amounts to about 1000 W/m².

The global radiation in turn is made up of the following three parts:

- Diffuse radiation:
  Diffuse radiation is the part of radiation, which results from the reflection of sunlight off of dust particles or gas molecules. The reflection causes the solar radiation to be diffused and it hits earth’s surface undirected and with less intensity. Not every type of solar panel can absorb this diffused radiation.

- Direct solar radiation:
  This part of radiation is the part of radiation, where the sunlight hits the earth on a clear day. The radiation can thus be absorbed by every solar collector and turned into heat.

- Reflected sunlight:
  Reflected radiation is the part of radiation, which is first reflected by another object such as a house and then hits the solar collectors undirectedly.

3.3.3.2. Solar coverage rate

The solar radiation during winter is at the lowest, when the heat demand is at its highest. This fact is a bad precondition to heat buildings exclusively with solar heat. Such monovalent operated plants have already been built for research purposes, but have shown a bad relationship of use and expense. In our latitudes, the use of solar energy is therefore mostly used in combination with another energy source (oil, gas, wood, electricity, etc.). In these types of plants, the solar energy should only supply a part of the needed thermal energy. Thus, the solar plant has to be designed so that the use/expense-ratio is worthwhile for investors. The amount of the annual thermal energy demand covered by solar radiation is called solar coverage rate.
A few characteristic values for the solar coverage rate depending on the use of solar energy:

- **Hot water production:**
  If the solar plant is solely used for hot water production, then the plant is sized so that the solar coverage rate is at 100% in summer. In winter, the room heating needs to be reheated either via heat generator (e.g., boiler, heat pump) or electrically.

- **Hot water production and room heating:**
  A solar coverage rate of 40% can be reached with currently typical constructions with regards to the use of solar plants for room heating and hot water production. Higher results are possible, if the heat loss of a building is reduced by means of better insulation or installation of a big – often uneconomical – solar plant.

- **Open-air pools:**
  Open-air pools can be exclusively heated with solar heat, if the occasional usage restrictions are taken into account, for example during longer periods of bad weather.

![Solar coverage rate for domestic hot water](image)

**Fig. 3-15** Example-Diagram of solar coverage rate for domestic hot water generation (source: Heizsparer)

### 3.3.3.3. Structure and operating principle of solar panels

The structure and operating principle are explained with help of flat plate collectors. The flat plate collector is the most used collector type. The most important components of such collectors are:

- **Absorber:**
  The absorber should be able to absorb as much thermal radiation as possible and reflect only little, so that the efficiency is as high as possible. Furthermore, it should provide for a good heat exchange to the heat transfer fluid.

- **Glazing:**
  This cover should let through as much solar radiation as possible, but should keep the reflection of heat of absorbers and heat loss by means of convection low.

- **Housing:**
  The sheet metal housing should have a good insulation, so to keep heat losses as low as possible.
The sun rays penetrate the glass cover and hit the black surface of the absorber, where the radiant heat is absorbed as completely as possible. Then, this heat is delivered to the pipes attached to the absorber, wherein the heat transfer fluid is circulating. The absorber surface is heated to up to 100 °C. The heat transfer fluid absorbs the heat and transports it via solar circuit to the heat exchanger.

3.3.3.4. Construction methods

The main types of solar collectors used today are flat plate collectors or tube collectors.

**Flat plate collector with selectively coated absorber**

This construction method minimizes the heat losses by means of insulation made of rigid foam insulation or mineral wool. The absorber absorbs almost all the sun rays and thus has small radiation losses. The pricing of such collectors is low, compared to others. In addition, on-roof or in-roof mounting is possible. There is a risk of condensation forming on the glazing.

**Vacuum flat plate collector**

The heat conduction losses are very low thanks to the vacuum in the collector. It practically has no convection losses. There are no dust deposits or corrosion in the collector because of the vacuum. Furthermore, it is impossible for condensation to form. However, the expenses for this collector are noticeably higher than those of the flat plate collector. Moreover, no air must enter; otherwise a new vacuum has to be created.

**Vacuum tube collector:**

Here, the absorber is built into a glass tube with a diameter of about 65 to 100 mm. There is a vacuum in the tube on both sides of the absorber surface. The vacuum prevents convection in the collector and thus the heat loss between absorber surface and glass is very low.
A heat exchanger tube is installed on the absorber surface of every glass tube, in which the heat transfer fluid circulates. The absorber subsequently transfers the heat via heat exchanger tube. This construction method primarily stands out because of its very low heat losses and therefore its high efficiency. The absorber can be rotated and consequently be adjusted towards the sun. The higher efficiency means less space required at the same output compared with flat plate collectors. The collector expenses, though, are very high.

![Vacuum tube collector](source: Vacano)

### 3.3.3.5. Heat transfer fluid circuit

The heat transfer fluid circuit provides the heat transfer from collector to storage tank. Its basic components are as follows:

- Solar collectors
- Closed piping system with fittings
- Circulation pump
- Safety unit
- Control and monitor device
- Heat exchanger

![Solar station with its components](source: PAW GmbH)
Solar stations are often used. They already entail all the important components needed to operate solar plants. Consequently, only the collectors as well as the heat exchangers need to be connected.

It makes sense to equip the tank with two solar heat exchangers, primarily in larger plants with a large storage tank and high collector temperatures or media temperatures. Thus the cold water in the lower part of the storage tank can be preheated, in case of little solar radiation and therefore low temperature of the heat transfer fluid. If higher temperatures are available in the solar collectors, the valve (6) is switched and the heat transfer fluid flows first through the upper heat exchanger and heats the hot water up to the desired temperature. After that, the cooled heat transfer fluid flows through the lower heat exchanger, to preheat the cold water.

![Diagram of solar plant with storage tank and heat exchangers](image)

High media temperatures in the heat transfer fluid can be reached by means of the low-flow principle. There is also a high-flow principle.

- **Low-flow:**
  With this principle, the flow speed is selected to be as slow as possible and usually executed with the help of speed-controlled pumps. This means that the heat transfer fluid stays in the solar collector for a longer period of time and thus is heated to higher temperatures.

- **High-flow:**
  In this principle, the flow speed in the pipes is set higher. Therefore the heat transfer fluid in the collectors flows at a higher speed and is thus heated to a lower temperature. A significantly greater quantity is pumped through the circuit, though.

### 3.3.3.6. The storage tank

Hot water is mostly needed in the mornings and evenings. The greatest quantity of solar energy, though, is available around noon or soon thereafter. In solar plants with heating support, the heating energy during the transition periods is only needed in the afternoon, too. The storage tank makes sure that the heat is stored in a case of surplus and discharged when the demand rises again. Assume 50 to 100 l storage volume per m² collector surface to act as a rough guide. For plants with room heating and hot water, the upper limits apply. For pure warm-water plants, the lower limits apply. In the case of a single-family house, consequently, hot water storage of about 350 to 500 l or a combined heat and hot water storage of around 1,000 to 2,000 l is needed.
3.3.3.7. Example of solar plants

Bivalent plant for room heating and hot water

In a bivalent plant, the solar circuit takes over the biggest part of the heat generation for hot water as well as for room heating during the transition period in spring and autumn. In summer, the entirety of the energy demand for hot water can be covered by the solar plant. The additional heat generator is consequently only used in winter and thus is well utilized.

Fig. 3-22  Example of a bivalent solar plant with conventional heat generators and distribution system for room heating and hot water

1 Combination storage tank  
2 Solar collector  
3 Circulation pump  
4 Temperature sensor  
5 Controller  
6 Heat exchanger  
7 Boiler (heat generator)  
8 Heat consumer
The conventional system (B) is complemented with a solar section (A). The generated solar heat in the collector (2) is given off to the storage tank (1) via heat transfer fluid circuit. The boiler (7) supplies additionally required heat in case of insufficient storage temperature. The heating water, which is heated in the storage tank, circulates directly through the heating surface (8), and also indirectly heats the domestic hot water in the heat exchanger (6).

**Direct solar heater for industrial processes or hot water preheater in continuous flow process**

In the case of constant heat consumption, the solar heat can be used directly. The solar heat generated in the collector (2) is lead to the heat exchanger via heat transfer fluid circuit. The solar heat is then transferred from the heat exchanger to the secondary heating network, where the return flow is preheated. As soon as the temperature is sufficiently high, the now preheated return water can be directly reused by means of the switch valve.

![Diagram of direct solar heater](image)

**Fig. 3-23 Direct solar heater**

1  Heat exchanger  
2  Solar collector  
3  Circulation pump  
4  Temperature sensor  
5  Controller

**Larger plant for hot water preheating**

This principle is often used in larger plants with high hot-water consumption (hotels, sports facilities, etc.). This is why these types of plants often have two hot water storage tanks at their disposal. This way, the solar heat collected in the solar collector (2) can be lead to the preheater (1.1) via the heat transfer fluid circuit. In the preheater, the heat is transferred to the cold water via internal heat exchanger and the cold water is preheated. If the collector surface is big enough, it is possible that the entirety of the energy demand in summer for hot water generation can be met. In winter, when solar radiation is low, the conventional heating plant can be used to reheat. If solar energy should not be sufficient, then the temperature in the water heater (1.2) is too low. This means that it is necessary to reheat with the heater. For this purpose, the possibly preheated water is lead through the external heat exchanger (see chapter 3.5.3.1 Domestic hot water storage tank for functions) and reheated there, so that it can be used again afterwards.
3.3.4. Heat pump (HP)

3.3.4.1. Function
The heat pump is identical to the technical structure of a refrigerator (see chapter 4.4). The operating principle is also the same, with the exception that the heat pump uses the condenser side, or rather the warm side, while the refrigerator uses the evaporator side, or rather the cold side. The operating principle of compression, absorption and adsorption refrigerators is covered in chapter 4 Refrigeration technology.

3.3.4.2. Heat sources

Water
Ground water has the capacity to keep an almost constant temperature of 8 °C to 12 °C all year round. This means that the temperatures on the evaporator side are high, even in winter. This, in turn, has a positive effect on the efficiency rate. Lake, river or waste water can be used in addition to ground water.

Air
The air temperature undergoes great temperature fluctuations in the course of a year. In winter, in the times of great heating demand, the outdoor air is at its coldest, which has consequences on the efficiency rate. The warm exhaust air from machines could also be used.
Soil
As with ground water, the soil also has a relative constant mean annual temperature from a depth of 1 to 2 meters onwards. The mean annual temperature lies at about -3 °C to 3 °C. The heat of the soil is made useful by means of a brine transfer cycle (water-glycol mixture) managed in separate pipes.

3.3.4.3. Different designs
Air/water heat pumps
Air/water heat pumps source the evaporation heat from the air. Outside air is used for the most part. Exhaust air can also be used, as its temperature is usually higher than the ambient air’s is. Air/water heat pumps exist in these two design variants; compact unit or split unit.

The compact unit contains the evaporator and condenser unit of the same appliance. This can be set up on the inside as well as the outside. In the case where the compact unit is set up on the inside, the ambient air is either lead through an air duct or an air pipe into the heat pump. The split unit is made of two separate components. The fan and the evaporator make up one component. This component is normally installed on the outside and connected with the second component – which entails the compressor, the condenser as well as the expansion valve – via refrigerant line. The latter is situated in the heating plant. At evaporation temperatures of 0 °C, frost and ice will form on the evaporator, which then has to be defrosted occasionally. When the temperature of the ambient air is low then the efficiency rate and the COP will drop considerably. This is why an air/water heat pump is a poor choice for a monovalent operation. It would be better to use the air/water pump in a bivalent plant, where an additional boiler is used at low ambient temperatures.

Brine/water heat pump
In the brine/water heat pump, an antifreeze solution (glycol) needs to be added to the water cycle of the evaporator side to prevent the heat transfer fluid from freezing. This mixture of water and glycol is also called refrigerant brine.

The following two ground-heat extraction systems are used often: ground heat exchangers and borehole heat exchangers. The ground heat exchangers extract heat via a coil piping system, which is set up around 20 cm below the frost line (e.g.: 2 m underground). They however require a large area. These collectors require roughly double the space of the respective living area. Borehole heat exchangers extract heat from the ground in a vertical matter. They are mostly between 100 and 300 m long. The load of these borehole heat exchangers should be less than 45 W/m. Because of the constant temperature in the primary circuit, this is suitable for monovalent operation. What needs to be taken into consideration, though, is that a simulation calculation is needed for greater heat capacity, i.e. if more than four borehole heat exchangers are used, so to make sure that the ground doesn’t cool down too much. An alternative would be to use the waste heat to “recharge” the ground during summer, when the building needs to be cooled.
Water/water heat pump

The ground water is extracted by means of a system of pipes to pump water. Then, the water is lead to the evaporator and on to the pipe which leads the water back to its source. Due to the risk of the evaporator being polluted, an intermediate circuit is placed between ground water and evaporator. A constant and most of all high temperature on the primary side is available in this case as well. That is why this heat pump is suitable for both a monovalent as well as a bivalent operation.

3.3.4. Operating modes of heat pumps

Monovalent operation

In monovalent operation, the heat pump is the only heat generation that covers the power demand. This type of operation is especially useful for when the temperature on the evaporation side is constant. This particularly applies to brine/water and water/water heat pumps. An air/water heat pump can also be used monovalent in smaller plants with less heat output, whereby the efficiency rate is very low and thus oftentimes needs an additional heater (electric).
Bivalent-parallel operation

In the bivalent-parallel operation, the heat pump covers the heating requirements up to a certain outdoor temperature. At lower temperatures, the additional heater is switched on and the two heat generators work in parallel, and together, they cover the required heat output.
Bivalent-alternative operation
Here, too, the heat pump covers the heating demand up to a certain outside temperature. At lower temperatures, an additional heat generator takes over and covers the heating requirements by itself. Thus, in this operation it is switched between heat pump operation and additional heat generator.

Fig. 3-30 Heating plant of a bivalent-alternative heat pump
1 Heat pump  2 Storage tank  3 Boiler

3.3.4.5. Storage tanks
Compared to a boiler, the heat pump is a dynamic heat generator and its heat output is dependent on marginal conditions such as outside and system temperature. Thus, the transmitted heat from heat pumps and the required heating output on the part of the building can vary. Furthermore, the switching frequency of a heat pump should be as small as possible and thereby the operating time of each circuit respectively long, because each activation constitutes a heavy burden on the compressor. These are the two main reasons as to why a storage tank should be installed. Here, there are two possible option of storing:

Technical storage tank
- Reduction of the switching frequency and thus greater durability of the compressor
- Hydronic decoupling between generator circuit and consumer circuit

Heat storage tank
- Reduction of the switching frequency and thus greater durability of the compressor
- Hydronic decoupling between generator circuit and consumer circuit
- Bypass during longer off-time
- Utilization of low-rate electricity
- Bypass during supply gaps of heat source
3.3.5. Cogeneration or combined heat and power (CHP)

Cogeneration or combined heat and power (CHP) is a process in which heat and electricity is generated simultaneously. The term dates back to a time when industries used steam engines to generate power for the machines and then heated with the exhaust steam. You would have to call it combined heat and power (CHP) today. The term “cogeneration” is still in use, though, and isn’t exclusively used in building technology.

3.3.5.1. Cogeneration types of application

A short overview of the types of application:

- **Steam turbine + Generator:**
  First of all, the steam turbine and generator combination is used for the power generation in nuclear power stations and conventional thermal power plants. The produced waste heat is used for the improvement of the total utilization rate, if a district heating plant can be served.

- **Gas turbine + Generator:**
  The gas turbine and generator combination is also primarily used for power generation. It uses waste heat, the same as with the steam turbine.

- **Cogeneration plant:**
  Here, the waste heat of a combustion engine is used. The engine powers a generator, which in turn generates power. The sizing of the cogeneration plant is layed out according to the required heat output.

The cogeneration plant is mainly used in building technology.

3.3.5.2. Cogeneration plant

Combined heat and power units are cogeneration plants for the use in commercial buildings, hospitals, industrial companies or for local heating of housing estates. The combined heat and power unit can be used in monovalent operation when operating smaller plants. Bivalent operation should be pursued with larger plants, so that a boiler can be switched on at peak power demand. An economic operation time as well as a reduction of switching frequency is strived for with heat storage tanks. If only heat and no power is required, the excess thermal energy can be stored in the heat storage tank. If, on the other hand, the demand for heat is greater than the simultaneous demand for energy, then the rest of the electrical power could be forwarded to the public electricity network.

Fig. 3-31 Schematic diagram of a plant with cogeneration (source: EnergieAgentur)
A cogeneration plant entails:

- a combustion engine (gas or diesel engine)
- a heat recovery component for the use of the engine waste heat (cooling water, exhaust gas and maybe lubricating oil) on different temperature levels
- a generator for power generation

The combustion engine could use natural gas, heating oil, sewage gas, bio gas, landfill gas or pyrolysis gas as engine power.

**Advantages of a cogeneration plant**

If heating oil or gas is burned to create power in a great thermal power station, the efficiency rate of the power generation is only at about 40%. The rest would be lost to the environment in the form of exhaust heat. The exhaust heat could be brought to consumers by means of district heating if these consumers should be in close proximity to the power station. The latter are very rarely stationed so close by potential consumers, though, so an expansion of a district heat supply system wouldn’t be very profitable. This means that the exhaust heat is often still lost.

Cogeneration plants can be flexible and thus built in immediate proximity to the consumer. This means that a cogeneration plant can either be used decentralized in the area of local heating for multiple consumers or it can be fitted in a single building. In these kinds of cogeneration plants, about 30 to 35% can be used as high-quality energy. About 50 to 55% can be used as heating power for radiators. This accumulates to an efficiency rate of 80 to 90%. The fact that cogeneration generate large amounts of noise emission due to the combustion engine needs to be taken into consideration. Therefore, any local regulations need to be observed.

**Application of a cogeneration plant**

Cogeneration plants are either used to cover personal demand for heat and electricity or are applied in local heating supply. It is important that both forms of energy are needed simultaneously and in arising proportions. A cogeneration plant can also partially or fully replace a separate emergency power supply.

**3.3.5.3. Micro and mini combined heat and power units**

A micro and mini combined heat and power (CHP) unit, respectively is a cogeneration plant which is used in smaller plants as for example in single-family houses or in multiple-dwelling units. It delivers the required heat output and a part of the electrical power. Micro-CHP units provide electrical power up to 15 kW, while mini-CHP units supply between 15 and 50 kW. Cogeneration plants provide around double to 2.5 times of the electrical power as heat output.
Modern mini-CHP units are equipped with speed-controlled engines and contain the necessary power electronics to feed the generated power back into the grid at a constant frequency. Due to the speed-control, additional installations to cover for peak loads are not needed anymore. These mini-CHP units can also be run in monovalent operation, which respectively lowers capital costs.

In 1839, the English physicist William Robert Grove discovered that electrical power can be won from hydrogen with the help of fuel cells. He described this effect as electrolysis in reverse. His research didn’t gain much attention, though, as people were more interested in further developing the steam engine. People only started to concern themselves more intensely with fuel cells by the end of the 20th century and currently are trying to refine them.

3.3.5.4. Fuel cells
In 1839, the English physicist William Robert Grove discovered that electrical power can be won from hydrogen with the help of fuel cells. He described this effect as electrolysis in reverse. His research didn’t gain much attention, though, as people were more interested in further developing the steam engine. People only started to concern themselves more intensely with fuel cells by the end of the 20th century and currently are trying to refine them.

Operating principles
Fuel cells directly transform the chemical form of the stored energy in the gaseous fuel into electrical power and thermal energy. A fuel cell is essentially made of an anode and a cathode, which are separated from each other by an electrolyte membrane. The resulting energy is used via the fuel hydrogen H₂, when hydrogen ions H⁺ combine with oxygen ions O²⁻. As a result, hydrogen H₂ is lead into the anode, where it breaks down into H⁺-ions and negative electrons. Then, the H⁺-ions are able to flow directly through the membrane into the cathode. There, they combine with the ionized oxygen O²⁻ to form water H₂O. The electrons can’t go through the membrane, due to their negative charge. That is why an excess of electrons builds up in the anode. If you then combine the anode with the cathode, electrical energy flows. Energy isn’t the only thing that is produced in this process. During the chemical reaction, thermal energy accumulates, as the process comes about in high temperatures. This heat can thus be used for room heating.
Advantages

- **High electric efficiency:**
  The fuel cell can reach an efficiency rate between 53% and 60%, depending on the type.

- **Broad performance spectrum:**
  On the other hand, depending on its type, a fuel cell can produce electrical power from a few watts up to multiple kilowatts.

- **Low pollutant emission:**
  Mostly steam is created when using hydrogen as fuel. Carbon dioxide (CO₂) forms only when carbonaceous fuels (CxHy) are used. The carbon footprint is significantly lower due to the higher efficiency rate as the one from the classical heat engines.

- **Low operating costs:**
  Fewer plant parts means lower maintenance and operating costs.

- **Quiet:**
  Less mobile plant parts ensure a low noise emission.

Types of fuel cells

The various types of fuel cells are divided according to type of electrolyte membrane. It can either be fluid or solid, which provides the characteristic feature for:

- Demands for kind and purity of fuel and oxidizing agent
- Operation temperature
- Design
Essentially, seven types of fuel cells are in use today:

<table>
<thead>
<tr>
<th>Description</th>
<th>Electrolyte:</th>
</tr>
</thead>
<tbody>
<tr>
<td>alkaline FC (AFC)</td>
<td>Caustic potash</td>
</tr>
<tr>
<td>Polymer electrolyte membrane FC (PEMFC)</td>
<td>Polymer membrane</td>
</tr>
<tr>
<td>Direct methanol FC (DMFC)</td>
<td>Polymer membrane</td>
</tr>
<tr>
<td>Direct formic acid FC (DFAFC)</td>
<td>Polymer-Membrane</td>
</tr>
<tr>
<td>Phosphoric acid FC (PAFC)</td>
<td>Phosphoric acid</td>
</tr>
<tr>
<td>Molten carbonate FC (MCFC)</td>
<td>Molten carbonate</td>
</tr>
<tr>
<td>Solid oxide FC (SOFC)</td>
<td>Ceramic electrolyte</td>
</tr>
</tbody>
</table>

FC = fuel cell

The following two types are establishing themselves for the use in the area of residential houses:

- Polymer electrolyte membrane fuel cell (PEMFC)
- Solid oxide fuel cell (SOFC)

**Structure**

Compact units are primarily in use in residential houses. Normally, that entails a storage tank for domestic hot water production as well as a buffer storage tank. The unit is not designed to cover 100% of the load, which is why an additional gas condensing boiler is installed to cover the peak load. The inverter transforms the direct current into an alternating current and thus makes it serviceable for the consumer. With the help of a catalyst, the reformer converts the natural gas into hydrogen ($\text{H}_2$), which later acts as fuel, and carbon dioxide ($\text{CO}_2$).

![Fig. 3-35 Structure of a fuel cell boiler (source: Viessmann)](image_url)
### 3.3.6. District heating

The thermal energy for district heating is generated in a centralized location or used as waste heat and transported via piping networks to the various central consumers. Next to room heating, thermal energy can also be used for hot water heating and industrial processes. Thus, whole neighborhoods or city districts can be supplied with thermal energy.

District heat essentially entails the following four plant parts:
- Heat source (heat plant, cogeneration plant or use of waste heat)
- Distribution network through transport pipes and local networks
- Transfer stations, where the heat is either directly or indirectly transferred to the consumer
- Consumer (households or business entities)

**Fig. 3-36 District heating system with the four heating plant parts (source: Geothermie St. Gallen)**

1. Heat source (cogeneration plant, geothermal CHP plant)
2. Distribution network
3. Transfer station
4. Consumer (household, industry)

#### 3.3.6.1. Heat generator or use of waste heat (heat source)

**District heating plants**

District heating plants exclusively produce thermal energy. This can be done by means of burning fossil fuels, namely gas or oil. Nowadays however, these kinds of district heating plants are more commonly operated with the solid material of wood whereby wood chippings, pellets or other wood by-products are used in particular. Moreover, large-scale heat pumps, which generate the necessary thermal energy in district heating plants are currently often in use (see Fig. 3-37).

**Cogeneration plant (combined heat and power)**

Cogeneration plants primarily generate electrical power, where the accumulated waste heat can be used for heating purposes. The combined heat and power units, where the engine waste heat is used, can act as a thermal energy supply. Waste-to-energy (WTE) plants, which mainly produce steam so to power the turbines, also accumulate waste heat, which can subsequently be reused as district heat.

**Industrial waste heat**

Here, the thermal energy is won from the waste heat produced by industrial processes. These processes represent the melting of metals in furnaces.
3.3.6.2. Heating media

Suitable heating media are warm water, hot water or steam. District heating plants which use steam are not commonly used anymore, as the condensate recirculation is very arduous and temperature control depending on outdoor temperature is impossible. Nowadays, most of the district heating networks are operated with warm water networks, because the demand for hot water is not in great demand anymore. Furthermore, the losses in warm water networks are much lower and the safety-related requirements are fewer. Moreover, the system temperature of warm water is just easier to control. This is often done subject to the outdoor temperature, whereby there is a minimum temperature. The operator usually requires a maximum return flow temperature, so that the delivered heat is used as efficiently as possible.

3.3.6.3. Heat transport and distribution (distribution network)

The heat transport between heat source and the consumers is organized via district heating distribution network. This is usually a closed circulation system. The distribution network can also be extended to a 2-wire or 3-wire connection. The distribution network in the 2-wire connection entails a supply line and a return line. The 3-wire connection possesses two supply lines; both of them have different system temperatures. This means that consumers, which require a consistently high system temperature, as well as consumers, which require a variable temperature, can both be supplied in parallel.

The following network structures exist as district heating distribution systems:

- Radial network
- Ring network
- Meshed network

Radial network

The radial network is a simple distribution system. The individual consumers are supplied by the central heat source via radial distribution lines. Due to the direct development, the construction costs are relatively low. The security of supply, however, is also low, because in case of an outage of the heat source the heat supply would be disrupted. Also, during reparations of one network, all the consumers, which are dependent on one branch, can’t be serviced anymore. Radial networks are often used for smaller supply areas.
**Ring network**

The great advantage of a ring network compared to a radial network is that a consumer is serviced from two directions in the ring network if two heat sources are available. Thus, the security of supply is greater. The distribution network is often used in larger supply areas.

**Meshed network**

This network provides the greatest security of supply. However, this distribution network also has the highest construction costs. It is mostly used in small areas, where the heat demand is great. This is often the case in city centers.

The network is laid depending on topography, local circumstances and soil conditions. The complete distribution network is isolated so to keep the distribution losses at a minimum. The flow temperature is operated variable in function of the outdoor temperature. Optimal flow speed and a great temperature spread between flow and return flow aim at minimal total costs of the distribution network.
3.3.6.4. Transfer station

The transfer station is the link between the consumer plant of the individual consumers and the distribution network. Due to the kind of connection, there are two different supply lines; an indirect and a direct supply line. Compact units are especially suitable for consumers with low load values.

Indirect power transfer

In the indirect power transfer, the costumer plant and distribution network are hydronically completely separated by means of a heat exchangers. Thus, distribution network and costumer plant are independent from each other concerning pressure and temperature, which can have advantageous effects on layout and operation of the networks. Both parties (suppliers and recipient) can operate their plants according to their needs. This version is a bit more expensive and requires more space.

Direct power transfer

In the direct power transfer, the heat transfer medium circulating in the distribution network flows through the transfer station directly into the heating circuit of the consumer plant. This is a relatively cost-effective and space-saving type of connection. It is aspired to, when a hydronic disconnection between primary and secondary cycle on the basis of pressure or temperature demands is not needed.
Compact unit

Compact units for consumers with low connected load such as single-family houses or multi-dwelling units are transfer stations, which are prefabricated in the factory. They are completely wired and tubed. This means that they possess a pressure control, a control valve and a heat meter depending on the design. On the secondary side, they also possess a heat exchanger and a circulation pump. They are easy to mount and don't take up a lot of space.

Fig. 3-43 Compact unit (source: BMS-Tech)
3.4. Important components

3.4.1. Pumps

Pumps are responsible for the transport of the essential water volume from heat generator to heat consumer i.e. for the heat output in a heating plant. This has to take place with as small a heat and energy loss as possible. The pressure losses created by pipelines, construction parts as well as fittings have to be bridged. Generally, centrifugal pumps are used. Due to the impeller blades rotating, the water is put into rotary motion, as well. The resulting centrifugal force pushes the water outward. Negative pressure arises in the center, which ensures water to constantly flow. The water directed outward is rerouted in the enclosure and thus the motion energy is transformed into pressure energy.

3.4.1.1. Designs

Two different designs of centrifugal pumps are used in heating technology:

- Glandless circulator pump
- Glanded circulator pump

Glandless circulator pump

The design and engine housing distinguishes glandless circulator pumps. All mobile components are simultaneously cooled and lubricated by the heating water. Theses pump designs are maintenance-free and silent.

Glanded circulator pump

Glanded circulator pumps are made as inline or base plate pumps. The engine as well as the water-bearing part is separated in this design. The impeller is connected with the engine via shaft. Here, a mechanical seal makes sure that the engine unit does not come in contact with water. This type of pump is not maintenance-free. The operating noise is higher than with the glandless circulator pump.

Fig. 3-44  Glandless circulator pump (left), inline pump (middle), base plate pump (right) (source: Grundfos)

3.4.1.2. Pump and plant characteristic curves

Each pump has its own characterization i.e., its own certain connection between volume flow and discharge head (also referred to as feed pressure). This is depicted with the help of the pump characteristic curve. The latter is determined by the manufacturer. Every plant also possesses its own plant characteristic curve (also referred to as piping characteristic curve). Here, the piping network resistance and the plant parts (pressure loss) depending on the output volume flow are illustrated.
Pump characteristic curve

As mentioned before, the pump characteristic curve shows the interaction between output volume flow and discharge head at a defined pump rotation speed (rpm) n. Thus, it indicates what kind of pressure flow can be bridged at a certain column flow or vice versa. A change of volume flow always means a change in pump pressure and vice versa. Thus, the available pump pressure decreases if the volume flow increases. If the resistance, which needs to be overcome, and thus the pump pressure rises, then the volume flow decreases.

Plant characteristic curve

The plant characteristic curve displays the connection between the volume flow and the resistance (pressure loss) either in a plant or in a piping network (which is why it is often called the piping network characteristic curve). An operating point can be identified with a certain pressure loss in a certain volume flow, e.g. at the design condition of a plant. Furthermore, the pressure losses of different volume flows can be calculated (quadratic dependence, see law of proportionality). With this, the characteristic curve can be charted. Piping networks with relatively wide pipings compared to the corresponding volume flow have a flatter characteristic curve. Pipings with smaller diameters compared to the corresponding volume flow have a steeper characteristic curve.

Operating point

Combine these two characteristic curves into one graph and it creates an interception point between two characteristic curves. This intercept is referred to as the operating point. The pump forwards the corresponding volume flow with the related discharge head at a constant rotation speed n according to the conditions of the operation point.
3.4.2. Actuating device (controlling element and actuator)

The actuating device is made up of the two components controlling element and actuator. The actuating device makes sure that the supply of thermal energy at part load for consumers is kept as low as needed – as per the standards and regulations. Different hydronic circuits are used for this purpose (see chapter 5.4). The so-called controlled ports located in the controlling element see to the required changes in volume flow.

3.4.2.1. Controlling element

You can distinguish between the following types of controlling elements:

- Two-port or three-port valve
- 2-way and 3-way ball valve

Two-port valve

The flow area in the two-port valve is reduced or increased via change of stroke. While doing so, the water volume – and thus the heat quantity – changes, which passes the controlling element.

Three-port valve

The three-port valve has three controlled ports, whereby one controlled port features a constant (AB) and two controlled ports (A, B) feature a variable flow rate. Thus, a change in the mixing ratio of various volume flows can reach the heat quantity. This happens in the three-port valve by mixing in colder water.

2-way ball valve

The flow area in the 2-way ball valve is changed via rotation of the ball. The water quantity – and thus the heat quantity – changes via controlled ball valve.

3-way ball valve

A mixing ratio between two feeds is created according the position of the ball in the 3-way ball valve. The relevant mixing ratio forms depending on the free flow area, which the respective feed has.
3.4.2.2. Actuator

The following can be used as actuators:

- Motorized drive
- Electrothermal drive
- Electrohydronic drive
- Magnetic drive
- Pneumatic drive (compressed air)
- Rotary drive

Fig. 3-50  Actuators: motorized (left), electrothermal (middle) und electrohydronic (right) (source: Siemens)

Fig. 3-51  Actuators: magnetic (left), pneumatic (middle) (source: Sauter), rotary drive (right)
3.4.3. Fittings for hydronic balancing

Hydronic balance makes sure that the pressure ratio and volume flow in the heating plant are synchronized in such a way that every consumer is supplied with heating water according to their needs during the desired state. It also lays the foundation for a functional operation of the plant as well as ensures a reduction of pump energy consumption and noise generation. A multitude of fittings which vary in their function and corresponding use can be used for this purpose:

- Balancing valves
- Flow controllers
- Differential pressure controllers
- Differential pressure controllers with flow control
- Pre-set radiator valves
- Lockshield valves
- Pressure-independent zone valves

3.4.3.1. Balancing valve

Balancing valves ensure mutual hydronic balance of groups or circuits. They are installed in proportion to hydronic circuits. They serve to set the volume flow in the desired state. Depending on the operation condition, the balancing valves reduce their force at part load and from then on act like ordinary resistance. The necessary settings depending on volume flow and pressure losses are provided by the manufacturers in the form of diagrams. Here, the adjustment needs to be performed by hand wheel.

![Fig. 3-52 Balancing valve (left) and flow controller (right) (source: Oventrop)](image1)

3.4.3.2. Flow controller

Flow controllers regulate the volume flow in a circuit according to the defined and set value. This takes place no matter what pressure ratios prevail in the plant. The desired volume flow is set according to an index. Subsequently, a membrane keeps the differential pressure constant according to a defined cross section by shifting the valve plug. This is why the volume flow doesn’t exceed the desired reference variable. Here, too, the adjustment is done by hand wheel.

3.4.3.3. Differential pressure controller

Differential pressure controllers ensure a constant differential pressure within a group or circuit in every operation status. The differential pressure controller is normally installed in the return line. It is connected with the supply line via impulse line so to measure pressure. Thus, the difference in pressure between supply and return line is measured. The latter is then kept constant with help of a valve plug. The valve plug depletes surplus differential pressure. Here, the setting happens via hand wheel, too.
3.4.3.4. **Differential pressure controller with flow control**

This fitting is a combination between flow controller and differential pressure controller. It keeps the differential pressure in the circuit constant and limits the flow to a set value. Thus this fitting provides a hydronic balance under all possible conditions.

3.4.3.5. **Pre-set radiator valve**

The individual radiators in heating plants with radiators need to be synchronized with each other. The difference between this fitting and the other balancing fittings primarily is the fact that the pre-set radiator valves create balance between multiple individual consumers while e.g. a balancing valve balances a complete group or circuit. There, the balance takes place according to a setting value. This setting depends on the desired volume flow as well as the necessary pressure loss by the consumer. The desired setting value can be taken from manufacturer diagrams via the two descriptions. This setting value can be set in the valve bonnet e.g. with a key.

3.4.3.6. **Lockshield valve**

The hydronic balance in radiators can be carried out via lockshield valve instead of the radiator valve. The safety cap needs to be removed first to set the lockshield valve. Then, you can also do the setting via key.
3.4.3.7. Pressure independent zone valves

Pressure independent zone valves are a combination between flow controller and differential pressure controller. They are applied at the level of heat output. Here, the differential pressure of the corresponding consumer is held constant in spite of flow changes. Consequently, hydronic balance prevails under any conditions and consumers are neither over- nor under-supplied.

![Pressure independent control valve PICV (left) and Mini combi valve (MCV) for radiators (source: Siemens)](image)

3.4.4. Safety-related equipment

Depending on the type of heating plant, different safety-related components need to be installed:

- Safety valve
- Safety temperature monitor
- Safety temperature limiter
- Expansion tank
- Intermediate vessel
- Low water safety
- Thermal safety valve

These components should protect the plant from the following possible operating situation:

- Overpressure
  The fluid heat transfer-medium expands when heating. This expansion needs to be safeguarded by measures in the plant. If the water couldn’t expand, it would lead to an extreme increase in pressure and plant parts would burst.
- Over temperature
  Various plant parts can be damaged by over temperature. When the temperature is too high in underfloor heating systems (e.g. floor heating) even the building construction can be damaged.
- Lack of water
  Lack of water leads to the danger of generated heat not being led away, which would lead to superheating in the generator. This is primarily important in central rooftop units.
Fig. 3-57  Typical safety installation in a hot water heating with closed expansion vessel

1  Safety temperature monitor (STW)
2  Safety temperature limiter (STB)
3  Safety valve
4  Expansion tank

Which safety-related components have to be installed depends on the corresponding country and its laws and regulations.

3.4.4.1. Safety valve

Every closed plant has to contain at least one safety valve. It protects the plant from overpressure. If the pressure in the plant should become too great in spite of the expansion tank, then the safety valve would take up its function as the last link of the safety chain. In case of emergency, the automatic opening of the valve discharges the entire heat output of the heat generator in the form of hot water or steam. The connection line should be constructed as short as possible and without noteworthy resistance. The outlet should be located in an area where people can't reside.

Fig. 3-58  Safety valve (source: IMI Hydronic)

3.4.4.2. Safety temperature monitor and safety temperature limiter

The safety temperature monitor (STM) turns the plant off as soon as the water temperature rises over a certain limit. If the temperature falls below this limit, the plant automatically turns on again.

The safety temperature limiter (STL) turns the plant off, if the temperature is too high. This state is also displayed (e.g. signal lamp, alarm signal...). Here, the limiter is locked in such a way that it can only be unlocked manually. Thus, someone needs to examine the situation on-site.
The expansion tank balances temperature dependent volume changes. The smallest temperature change would make heating water escape from the safety valve if it weren’t for the expansion tank. Mainly pressure expansion tanks with a rubber membrane are used. The membrane separates the water room from the gas room. The gas room is filled in the factory (e.g. inert gas) and is delivered with pre-pressure. This pre-pressure, which is dependent on static height, is intended to prevent too much water from getting into the tank the moment it is filled. If the temperature rises, the resulting expansion volume penetrates the tank against the gas pressure. If the temperature falls, the gas pressure on the membrane wall ensures that enough water flows into the plant. The pressure expansion tanks are measured in such a way that it can at least hold the expansion volume as well as the water reserve (hydronic seal). The size of the expansion tank is dependent on the following points:

- Water volume of the heating plant
- Maximum operating temperature
- Initial pressure
- Relieving pressure in the safety valve

Pressure maintenance system:

In plants with larger water content, expansion tanks with air compressors are used. The counter-pressure in the gas cushion is controlled via compressor and solenoid valve. A solenoid valve relieves air from the gas room if the water expansion is great. If the water contracts, the compressor leads air back into the gas room and thus upholds the needed counter-pressure. Therefore, the plant pressure will be inside the differential gap between maintaining via compressor and opening the solenoid valve. Plants such as these are usually delivered ready for use.
3.4.4.4. **Intermediate vessel**

There is a rubber membrane located in the expansion tank, which needs to be protected from too hot water to prevent accelerated ageing. This is why the expansion tanks (in addition to other criterias) are installed in the return line or rather on the suction side of the pump. That is because in the return line, the water temperature is lower than in the supply line. If even the maximum temperature of the return line is higher than 50 °C, then an additional not isolated intermediate vessel needs to be installed in front of the expansion tank. There, the water can cool down enough to not make the synthetic membrane parts age prematurely. Another reason to install the expansion tank in the return line is that the pump has a minimal inlet pressure to prevent cavitation in the circulation pump.

3.4.4.5. **Low water safety**

The low water safety is often used in heating plants wherein the center of the rooftop is located. It is intended to keep the heat generator from overheating or even burning out due to insufficient amount of water. The low water safety turns off the firing by means of a float, which is located in the water level limiter. This takes place as soon as the float goes below a minimum water level. It then locks itself against autonomous restarting.
3.4.4.6. Thermal safety valve

The thermal safety valve is installed in the solid fuel heat generator (wood boiler) and protects from over temperatures. In case of emergency, cold water will be lead through a heat exchanger embedded in a boiler by the thermal safety valve. An independent sensor in the boiler is connected to a thermally controlled valve in the cold water line with the help of a capillary tube. If the temperature transgresses the limit, the liquid in the capillary tube expands and ensures that the valve in the cold water line opens and thus the boiler is cooled with water.

Fig. 3-63  Diagram thermal safety valve

1  Lock fitting
2  Swing check valve
3  Thermal safety valve (self-acting)
4  Safety heat exchangers

3.4.5. Distribution systems

The water heated by the heat generator needs to be lead to the consumers. After the heat is delivered, the cooled return water should flow back to the generator. This cycle is supported by the distribution system. A distinction is made between:

- Distribution of the supply water:
  lower distribution, upper distribution, floor-wise distribution
- Piping systems:
  One-pipe system, Two-pipe system

3.4.5.1. Distribution of the supply water

Lower distribution

The supply distribution and the return manifold are lead underneath the consumer, e.g. on the cellar ceiling or in floor shafts. Riser lines vertically lead out of these pipes and supply the individual consumers on each floor. This distribution system requires little piping material than the upper distribution and thus is less expensive. Moreover, there is less heat loss. This distribution system however complicates the heat cost allocation as the respective riser lines are probably connected to various types of consumers (e.g. different companies in one). This means that there is no possibility to install a heat meter centrally, but there rather have to be calorimeters placed at each individual consumer.

Fig. 3-64  Diagram: Lower distribution
Upper distribution

Here, the riser line is placed directly above the highest floors of consumers. There, mostly in the attic, the respective stack vents are serviced. The consumers draw the heat from the heat of the stack vents. After the heat output, the return water is collected and lead back into the generator. This principle is often found in older, existing plants. In the past, it was often used in systems with gravitational heating. Nowadays, it is only seen in plants with central rooftop units. This system requires more piping material and leads to higher heat losses. The heat cost allocation is almost as complicated as it is in the lower distribution.

![Diagram: Upper distribution](image)

Floor-wise distribution

In this distribution system, each floor or each apartment has its own supply distributor as well as return manifold. These distributors and manifolds are often located in a distribution box built into a wall or in the floor. The distribution inside a building often takes place in the attic or through recesses in the concrete floor. The advantage of this distribution system is that one heat meter can be assigned to one consumer. This simplifies the heat cost allocation. The pipe connection, however, is twofold from the distribution box on to the consumers. This means that more piping material is required and thus this distribution system is more expensive.

![Diagram: Floor-wise distribution](image)

3.4.5.2. Piping systems

Two-pipe system

The two-pipe system is the heat distribution system that is used the most. Here, the water flows through the supply line into the heat output system and then back into the generator via return line. Each consumer therefore has almost the same supply temperature. Furthermore, radiators with the same size and temperature difference between supply and return for example deliver the same heat. The consumers also influence each other a bit, as each is supplied separately. The two-pipe system can be installed in combination with the upper, lower as well as the floor-wise distribution.
**Special type: Tichelmann system**

Here, the sum of the piping lengths from the generator to the individual consumer is almost always the same. This means that a radiator for example with a shorter supply line has a longer return line. Thus, all the consumers have about the same amount of heat losses and the static hydronic balance can be skipped. The plant is also more expensive due to the longer piping length.

![Diagram: Tichelmann system](image)

**One-pipe system**

One-pipe systems were often used in the 1970s to the 1980s. Back then, the system operating temperatures were much higher. The very low system temperatures of nowadays do not permit to reasonably plan a one-pipe system. Here, only one piping leads to a radiator. Hence, the radiator receives the supply water from this piping and then later leads it back into the same piping. This means that the first radiator receives the warmest and the last radiator receives the coldest supply water. This makes the planning very difficult and these low system temperatures lead to radiators becoming much bigger in size to ensure heat output. The one advantage is that it only requires a small amount of pipes.

![Principle of one-pipe system with multiple radiators](image)

**3.4.6. Heat output system**

**3.4.6.1. Radiator**

There are different types of radiators which primarily differ in appearance and the kind of heat output. This is why mostly surface radiators, sectional radiators or convectors are used nowadays. Furthermore, there are special radiators such as towel radiators or design radiators.

![Surface radiator (left), sectional radiator (middle), convector (right) (source: Zehnder)](image)
Heat transfer
Depending on the design and type of radiators, they give off heat differently. Thus, the heat of surface radiators primarily transfers via radiation and a small fraction via convection. In sectional radiators the heat is transferred more through convection and less through radiation. In convectors, as the name already indicates, the heat is transferred almost exclusively via convection. The respective fractions though are strongly influenced by the relevant radiator shape and are predetermined by the supplier.

Demands towards radiator
The main task of a radiator is to establish a comfortable room temperature. There are other aspects, however, which need to be observed in the planning phase:

- No sharp edges to avoid risk of injury
- Radiators should optically fit into the room
- They should be easy to clean
- As small as possible with the highest possible heat output
- Should be inexpensive, lightweight and easy to mount
- Heat output easy to control
- Should be installed in areas with great temperature differences (e.g. beneath a window)

Influences on heat output of radiators
The heat output data of radiators is measured in the laboratory according to standard specifications. Thus, the heat output is based on clearly defined basic conditions. Various influencing factors have an effect on the actual performance of a radiator in the respective environmental context:

- Temperatures
  The heat output is always measured according to the following standard specifications: supply temperature 75 °C, return temperature 65 °C and room temperature 20 °C. If any of these temperatures differ, then the effective heat output of a radiator needs to be calculated.

- Installation site
  The measured values always relate to the ambient pressure at sea level which is 1013 mbar. The heat output via convection, however, is dependent on air density. The air density, in turn, changes according to air pressure. Thus, the higher the altitude the lower the heat output of a radiator (convector).

- Color and coating
  The heat output of a radiator is measured with a normal coat of oil paint. The paint and coat have a great influence on the radiant heat output, which is expressed by a radiation coefficient. If the radiator has a different color or possibly a metal coating, the heat output needs to be calculated anew.

- Casing
  Radiator casings, covers, curtains or furniture reduce the air flow around the radiator, which leads to a drop in convective performance. These casings also have an effect on the radiant heat output.

- Type of connection
  Depending on the type of connection, the radiator has a different flow. Different circulations can result in “dead zones”, which have a negative effect on the heat output.
3.4.6.2. Floor heating

The heat in underfloor heating systems is almost exclusively transmitted via radiation. Therefore, the heat in the room is distributed conveniently. The most frequently used underfloor heating is the floor heating. The latter fulfills the need of humans for heat in the ground area. The goal here is an as even a surface temperature as possible. Floor heatings are typical for low-temperature heating systems and hence can be operated very cost-effectively in combination with heat pumps or condensing boilers as generators.

Systems

There are two different types of installation:

- **Wet installation**
  With a wet installation, the pipes are completely enclosed by the attic or cement coating respectively. Here, the heat is directly transferred to the attic. The feature of this system is the high inertia. Regarding the investment costs, the wet installation is less expensive than the dry installation.

  ![Installed floor heating pipes, installed wet (left) and dry (right) (source: hp praski)](image1)

- **Dry installation**
  Here, the pipes are installed in creases of the insulating layer beneath the attic. The pipes aren’t enveloped by the attic, which is why additional heat conducting lamellae are laid down to distribute heat more evenly. There is less inertia in this system. Due to the low installation height, this system is often used for renovations. The dry installation is more expensive than the wet installation.

  ![Heat conducting lamella in dry installation (source: Logafix)](image2)
Types of installation layouts for pipes

There are two types of installation layouts: the serpentine or rather meander-shaped layout and spiral layout. The spiral layout, in particular, distributes heat very evenly as the supply line and return line are located right next to each other and therefore create a constant mean temperature. In the planning phase of an installation, you have to keep in mind that the limit for a maximal surface temperature is not overstepped.

![Fig. 3-72 Serpentine (meander-shaped) layout](source: ikz) ![Spiral layout (right) (source: ikz)]

Advantages and disadvantages of a floor heating

Advantages:
- Particularly suitable for heat pumps and condensing boilers as generators due to the low heating water temperatures (max. 35 °C) and heat storage capacity
- Less conduit slits and thus less structural extra work
- Not visible in the room
- Small issues with placing of furniture

Disadvantages:
- Greater inertia and therefore poor controllability
- High costs in case of additional changes or repair work of the heating surfaces
- Restrictions concerning interior design (e.g. carpets) and flexible room division

3.4.6.3. Overhead heating

In the overhead heating, the heat is almost exclusively given off via radiation. The rooms should be over 3 m high, as heat radiation from above in low-ceiling rooms is often perceived as uncomfortable. In the past, the overhead heating used to be divided into two different systems: pipe overhead heating and radiant panel heating. In the pipe overhead heating, the heating pipes are set into the concrete ceiling. This principle is better known as ‘TABS’. TABS, on the other hand, works with low system temperatures (see 3.4.7 TABS – Thermo active building systems). The principle of radiant panel heating, however, has been developed further and can often be found in business establishments and industrial plants as well as sports centers, warehouses and factories. The radiant panel heating can in turn be divided into specific types:
- Closed ceilings
- Ceiling sail
- Radiant ceiling panels

Most of these can also be used for cooling.

Closed ceilings

This type of overhead heating requires a suspended ceiling made of metal or gypsum. Here, the respective ceiling is activated with the help of heating pipes on the topside. The architects create very artistic metal plates or gypsum boards. They can either be smooth or perforated. The metal ceiling can be installed in such a way as to make it accessible for service work, as the ceiling panels can be opened whenever needed. The gypsum ceiling on the other hand stays closed and can’t be reached without being damaged, but it can be installed seamlessly. This system is oftentimes simultaneously combined with acoustic measures or air diffusers. This type of construction can also be used as a chilled ceiling to cool rooms.
Ceiling sail
This type of construction is similar to the closed ceiling. The topside is also activated with pipes. Contrary to the closed ceiling, this construction doesn’t activate its whole surface but only individual parts called "sails". These sails can be installed either directly into the concrete ceiling or in suspended form. The sails are also available in metal or gypsum. With the help of a suspended ceiling grid, the sails can be embedded unnoticeably or rather integrated harmoniously into the overall design.

Radiant ceiling panels
The radiant ceiling panels can also be used in spaces with high ceilings. Their efficacy lies at up to 50 W/m². They are made of metal sheets with integrated pipes. Atop these metal panels are usually fitted with insulation. The panel lines can be installed one individual element behind the other. They are installed on the ceiling. If the radiant ceiling panels are installed in spaces with high ceilings, it has to be noted, that the radiant ceiling panels are operated with a sufficiently high supply temperature. This means that a temperature difference for the radiation exchange needs to be in place.
3.4.6.4. Wall heating

A wall heating with warm surface temperatures perfectly meets the requirements for thermal comfort, as its radiation reaches a significantly larger surface of the human body compared to floor heating or overhead heating. The heating pipes can either be embedded in concrete or coated by mortar. Insulation of the same quality as in floor heating is required behind the wall heating. This should especially be part of the outer walls, to prevent heat from escaping. The placement of furniture needs to be done consciously so to ensure that enough of the wall is left unobstructed. Wall heating is used rather rarely. It is however utilized in hotel spas and relaxation pool areas.

![Installed wall heating at outer wall (source: Wikipedia)](image)

3.4.7. TABS – Thermo active building systems

Thermo active building systems (TABS) are large scale, component-integrated or fitted heat or cooling output system. Systems such as these use the building mass, i.e. the floors and ceilings, for thermal air conditioning. Thus, room heating and cooling is either solely provided with the help of TABS or an additional system is used in combination with TABS. The thermally activated building components are systematically integrated into the energy management to increase energy efficiency. By activating great thermal masses, the heat and cooling output becomes inert. This has to be taken into account in the control as well as planning of TABS. Adjustments are made dynamically by means of the complete day and night cycle.

**Thermo active building systems**

TABS mean prefabricated pipe arrangements which are installed into the ceilings and have either a heating medium or coolant flowing through them. These pipe arrangements are made up of multi-layer pipes. This makes it possible to use the corresponding thermal storage mass. Heat is led by the water to the mass and then given off to the room while heating. Heat is taken from the room and lead back into the water via storage mass.

![Installed pipe arrangements in the ceiling (source: Tabs)](image)
Notes on installation

The individual pipe arrangements respectively entail a surface of about 15 m² up to 25 m². Theses pipe arrangements are installed together with other elements such as upper and lower reinforcement, electrical conduits, drain pipes and spacer blocks. This is why a good coordination between these different technical trades is important. Furthermore, a preliminary acceptance needs to take place before placing the concrete. Additionally, a pressure test of the arrangement has to be done. After placing the concrete, the arrangements can be connected.

![Thermo-active building systems (TABS)](image)

Fig. 3-78 Different TAB systems (source: Bine Information Service, FIZ Karlsruhe)

Each layer, located between the arrangement and the room, contains a thermal resistance. This means that plaster, insulation and intermediate ceilings are to be avoided if possible. The empty concrete ceiling surface can provide for a resonating effect, which often leads to greater challenges for noise insulation measures.

System temperatures

**Heating:** The ceiling heating had to be operated with high system temperatures in the past because of poorly insulated buildings. This then resulted in an uncomfortable temperature profile vertically along the walls of the room. As the buildings are better insulated nowadays, it makes it possible for the heating water temperature to lie between 24 °C and 28 °C. This leads to a comfortable radiation in the perception of the room users. Output densities of 25 up to 30 W/m² can be achieved in the area with these temperatures.

**Cooling:** System temperatures while cooling lie around 19 °C and 21 °C. That is how uncomfortable drafts can be avoided. The radiation of cold air is also comfortable and tolerable. The rather high cooling water temperatures allow for alternative refrigeration such as free cooling, also for a longer period during the year. Thus, the high energy consumption which refrigeration systems generate can be reduced. Output densities of 25 up to 35 W/m² can be reached. The possible cooling capacity in the upward direction is restricted by the dew point of the interior air.

Heating and cooling energy generators

Heat pumps, for example, can efficiently be used for heating due to the supply temperature being close to that of the room. Environmental forms of energy such as free cooling, recooling and groundwater or lake water cooling are preferred in addition to cooling provided by a refrigeration plant.

Integral planning of overall system

TABS in a building ensure a high room comfort. This is only achievable when combining carefully coordinated measures with the following basic elements:

- Integral planning is of great importance and indispensable in regards to a solid energy efficiency of the overall system
- Very good protection against heat and sun
- Sufficient thermal building storage capacity
- Air-tight building envelope with basic ventilation and air renewal necessary for hygienic purposes
- Heat recovery
- Correct hydronic design of the piping system
- Special TABS control strategy
Advantages

- Heat transfer (heating) as well as heat absorption (cooling) is done via thermo active building systems with their large transfer surface.
- Low system temperature differentials (thanks to large transfer surface)
- Efficient use of natural energy sources possible
- Delayed heat transfer and heat absorption
- Utilization of the night’s cool ambient air in summer
- Operation of heat pumps in time periods with low electricity costs
- Energy efficient heating water and cooling water production with self-controlling-effect of the room temperature
- Low installation and operating costs (similar to traditional systems)

Restrictions

- Observe the additional thermal inertia
  The additional thermal inertia needs to be observed in ceiling or floor constructions such as hollow floors, suspended ceilings or isolating sound insulation.
- No random requirements towards thermal comfort, meaning it needs to be tolerated that the room temperature will fluctuate during the day, within certain bounds
- Challenging integral planning
  The estimation of the heat load is important while planning and it often is appropriate to do simulation calculations.
3.5. Hot water processing

3.5.1. Introduction
The hot water processing produces hot water. This hot water is used for showering, bathing and washing. Due to the constantly growing comfort standards, the hot water processing is thus subject to very high demands. Moreover, the water's hygiene requirements have to be met at all times. Essentially, the demands are that hot water is available in the right amount and at the right temperature at all times. This hot water should be inexpensive, impeccably hygienic and not use too much energy while processing.

3.5.2. Centralized and decentralized supply
The supply of the extraction point (consumer) is either centralized or decentralized.

3.5.2.1. Decentralized supply
Decentralized supply can either be done via individual or group supply.

Individual supply
Each extraction point has its own water heater in the individual supply system. Almost no hot water pipes need to be installed with this system. The investment costs, though, are fairly high as there are many extraction points which require many individual units. When heating water serves as energy supply, then the piping needs to be laid towards the individual extraction point. The maintenance costs are high because of the many individual units.

Group supply
The term group supply describes when multiple extraction points within one zone are supplied by a single water heater in a supply system. Zones can either be an apartment or an individual floor, for example. The investment and maintenance costs for the water heater are lower. This system requires more hot water pipes than the individual supply system. Here however, the hot water supply network is clearly smaller concerning the primary energy supply with hot water.
In centralized supply systems, all extraction points of a building are supplied by the same water heater. As merely one water heater is required, the acquisition and maintenance costs are significantly lower compared to the decentralized supply. However, it needs a hot water distribution network that supplies the extraction points with hot water. The hot water distribution network needs to be insulated so to minimize the heat losses. It also requires a heat storage system (see chapter Error! Reference source not found.) so that hot water is available anytime at the extraction points.
3.5.3. Water heater

The hot water is heated either in a domestic hot water storage tank or a flow-through water heater.

3.5.3.1. Domestic hot water storage tank

The hot water is already heated in the domestic hot water storage tank before the extraction and then stored. Domestic hot water storage tanks can cover large volume flows if needed. The complete taken volume, though, is dependent on the storage volume. If the complete volume is taken in, then hot water is only available again after a certain amount of time (heating time). The storage volume can be laid out in such a way that it covers either the daily consumption of hot water or a certain time span. In case the daily requirement is stored, the storage volume is often heated during the night at a reduced heating mode. If the storage volume is laid out to a certain time span, then the heat generator needs to be able to heat water at any given time. Storing the hot water creates heat loss.

When storing the hot water, there is a danger of legionella bacterias building in the domestic hot water storage tank. These bacterias multiply the fastest if the water temperature lies between 25 °C and 50 °C. They die if the temperatures rise beyond 60 °C. That is why the domestic hot water storage tank needs to ideally contain hot water at 60 °C at all times or that the entire storage volume is heated to 60 °C periodically.

You differentiate the domestic hot water storage tank according to the placement of the heat exchangers; the storage tank water heater with an internal heat exchanger or the hot water storage tank with an external heat exchanger.

Storage tank water heater with internal heat exchanger

The storage tank water heater heats the hot water above integrated heating surfaces (heat exchanger). The hot water is then stored in the storage water heater. The storage water heater with an internal heat exchanger does not provide the entire volume as storage volume for hot water. The heat exchanger is located in the lower part of the storage tank. The cold volume is situated beneath the heating surfaces and the mixing volume is inside the heat exchanger. Thus, solely the volume above the heating grid serves as storage volume.

Hot water storage tank with external heat exchanger

The hot water in the hot water storage tank with an external heat exchanger is heated with an external heat exchanger. It is then stored in the hot water storage tank. Contrary to the storage tank water heater with an internal heat exchanger, the entire volume of the hot water storage tank can be used as storage volume. This system needs more space, though, due to the external heat exchanger. The acquisition costs are also higher, because of the external charging station.

Fig. 3-82 Storage tank water heater with internal heat exchanger (left) (source: Viessmann), Hot water storage tank with external heat exchanger (right) (source: Ygnis)
3.5.3.2. Flow-through water heater

The hot water is warmed directly during extraction in the flow-through water heater. The water is heated while it flows through the water heater. The temperature of the hot water is dependent on the volume flow and the heat output of the water heater. For example, if a lot of hot water is taken at limited heat output, then the hot water temperature is lower. This means that the flow-through water heater requires equivalently high heat outputs. As the hot water isn’t stored but warmed directly, the danger of contamination by legionella bacteria’s is minimized. Additionally, there are no heat losses on account of storing water. Circulation is not possible in the flow-through water heater (see chapter Error! Reference source not found. Error! Reference source not found.). This is why, depending on the piping length between the extraction point and the flow-through water heater, it can take long for hot water to be available. The most used design of a flow-through water heater are the instantaneous gas water heater or the fresh water station, which are either heated directly via heat generator or indirectly via heat storage tank.

Instantaneous gas water heater

The water in the instantaneous gas water heater circulates through a heat exchanger and is heated as a result. The required thermal energy is taken from the combustion of gas. An atmospheric burner is frequently used for this (see chapter 3.3.1.6 Gas burners). The heat output is controlled by the amount of gas. It needs to be observed that an instantaneous gas water heater requires an exhaust pipe.

![Instantaneous gas water heater (source: Ecotemp)](image)

Fresh water station, directly heated by heat generator

Fresh water stations essentially are heat exchangers. Here, the heat output is transferred from a primary heating water cycle to a secondary hot water circuit. The volume flow of the ordinary heating water is matched with the current hot water usage for control.

![Diagram: fresh water station for group supply, supply directly from heat generator](image)

1 Boiler 2 Extraction point (consumer)
3 Fresh water station  CW Cold water
SL Heating water supply
RL Heating water return
Here, the heating water is heated directly by the heat generator. The generator needs to be layed out correspondingly large in size so that it can cover the simultaneously arising hot water consumption.

**Fresh water station, indirectly heated by heat generator**

The principle of water heating is the same here as with the fresh water station that is directly heated by the generator. The difference lies in the primary thermal energy supply of the fresh water station. Here, the heat storage tank supplies the fresh water station. The heat storage tank possesses its own stored thermal energy, which can be used in case of great last-minute hot water consumption. Therefore, the heat generator can be sized significantly smaller. It keeps the temperature in the heat storage tank with a basic heat output.

![Diagram: fresh water station for group supply, supply indirectly by heat storage tank](image)

**3.5.4. Compensation of heat losses in distribution**

The heat losses of the distribution lines need to be compensated so that hot water is always available at the extraction point. This compensation can either be done by heating cables or circulation systems.

**3.5.4.1. Heating cable**

The heating cable is directly attached to the piping. The emitted heat output of the heating cable respectively adjusts itself to the local conditions. The heating cable is also self-regulating. One advantage is that the heating cables don’t take up a lot of space and the temperature stratification in the storage tank doesn’t interrupt. A disadvantage is that it requires electrical energy.

![Heating cable attached to piping](image)
3.5.4.2. Circulation systems

The heat losses in the circulation systems are compensated by the water heater. The water heater needs to be bigger in size for this purpose. In order to keep the heat losses minor, it is very important to have an optimal insulation for the piping. The biggest issue in circulation systems is the circulation lead-ins. If the circulation is lead back into the storage tank, there is a possibility that it will destroy the stratification in the storage tank due to temperature fluctuations.

Conventional circulation

The circulation line is lead separately up to the relevant extraction point, where the circulation still needs to be warranted.

Pipe to pipe circulation

The circulation line is directly mounted to the hot water line and both lines are insulated together.

Pipe in pipe circulation

The circulation line is lead in the hot water line. The hot water line should accordingly be layed out larger in size.
4 Refrigeration technology

4.1. Introduction

It is in the nature of things that human beings have been preoccupied with the subject of cooling since prehistoric times, and we know of many different possibilities of cooling. Liquids (such as wine) were cooled in clay jars wrapped with wet clothes or in canteens (heat extraction via evaporation of water). The Romans for instance used ice to keep food cool and fresh. They brought ice blocks down from the glaciers into cities and kept them in subterranean storage rooms that were insulated with straw. In the 19th century, the commercial use of natural ice (e.g., from frozen lakes) started. In the hot seasons, it was sold to wealthy customers by the ice man. Breweries too used ice for their different cooling processes during production, storage and delivery of the beer.

The initial considerations on the topic of refrigeration known to us originate from the year 1835. Jacob Perkins, an American inventor and mechanical engineer, patented a vapor compression machine operating with a closed cycle.

Some 40 years later, in 1876, Carl Linde, a German engineer and inventor, was the first to use ammonia as a refrigerant in a vapor compression machine with a piston compressor. First, this machine was mainly used in breweries as it allowed fermentation at constant temperatures without the use of natural ice.

The most known cooler is the domestic refrigerator. It first appeared in the year 1910. The demand for refrigeration originated in the food supply industry so to cool food products.

The demand increased greatly later, and a distinction came to be made between the following three fields:
- **Industrial refrigeration**
- **Commercial refrigeration**
- **Domestic refrigerators and freezer (domestic refrigeration)**

Today too diverse food products require refrigeration so to keep them fresh for a certain period of time, thus ensure basic supply.
Air conditioning also increasingly gained in importance. Thus, not only heating energy is required in winter, but it is also required for cooling and dehumidification of the air during the summer period. This ensures a comfortable room atmosphere and therefore an enhanced sense of well-being in a closed room.

Refrigeration can either be done with the help of free cooling, surface water or technically produced cold (cooling unit):

**Refrigeration with free cooling**
Free cooling describes the use of ambient air for cooling. Free cooling is used, when the temperature of ambient air is lower by a certain few degrees than the maximum room temperature. This is why it can be used in buildings with high heat loads (e.g. computer centers, shopping centers), particularly during transition periods. If for example the room temperature in shopping centers is to be 26 °C, then ambient air with a temperature of up to 20 °C can be used for free cooling. Depending on the dimensioning, computer centers can exclusively use free cooling for refrigeration.

**Refrigeration with surface water**
Surface water can for example mean ground water, river water or lake water. The temperature of surface water lies between 8 °C and 18 °C and is available in sufficient quantities. In the field of air conditioning, it is particularly used together with static cooling surfaces or thermo activate building systems (TABS). For this purpose, the surface water is collected and leads through a heat exchanger. The latter transfers the cooling energy to a second circuit, which then leads to the individual rooms where it supplies the cooling surfaces.

**Technically produced cold with cooling unit**
If for example no surface water is available or isn’t allowed to be used, then the cold can also be produced technically by means of a cooling unit. This unit can also be used in case the surface water’s temperature isn’t low enough. The cooling unit can be compared to the domestic refrigerator.

**4.2. Refrigeration with free cooling**
In free cooling, an appropriate medium is lead through a heat exchanger (mostly dry cooler) in a closed system. Fans blow cooler ambient air through this heat exchanger. The heat exchange takes place in the process which cools down the medium in the circuit. This medium then flows back into the room. There it releases the cold via heat exchanger (air cooler) before the warmer return flows back. The medium is mainly a water/glycol mix, so that it doesn’t freeze in low ambient temperatures.
4.3. Refrigeration with surface water

As mentioned before, the temperature of surface water, depending on the type, lies between 8 °C and 18 °C. These temperatures are often enough to cool a room or the air warmer than 20 °C.

Wet refrigeration of supply air

The surface water is collected and the cold is transferred to the secondary medium via heat exchanger (1). As a result, the warmer return water or the new fresh water is cooled. This cooler water then atomizes and evaporates in a chamber (2) in the ventilation unit. The heat, which is required to evaporate the water, is taken from the air. That is why the air cools down. The air is subsequently released into the room via outlet (3).

Dry cooling of supply air

Surface water again is collected and the cold is transferred to the secondary medium via heat exchanger (1). The warmer return water is cooled down in the heat exchanger. The cooler supply water then circulates through a heat exchanger (air cooler) in the ventilation unit (2). There, the air cools down afterwards. The air is released into the room via outlet (3).
Static cooling via cooling surfaces
Surface water is again collected. The cold is transferred onto the secondary medium via heat exchanger (1). There, the warmer return water is cooled down. The colder supply water is then lead into the room via cooling surfaces (2). The cold in the rooms is in turn transferred to the surroundings via radiation and convection.

![Diagram of refrigeration via cooling surfaces](image)

In short:
- Water gives off cold to cooling ceilings
- Warmer water flows back to the heat exchanger
- Closed system

Advantages of cooling with surface water
- Simple plant design
- If available: energy source water available as needed and free of charge
- No additional energy required (except for pumps and control device)

Disadvantages of cooling with surface water
- Energy source water isn’t available everywhere
- Fluctuating water temperatures
- Extraction of surface water requires an official permit
- Depending on location; complex and expensive development

Provided that the temperatures of the surface water don’t suffice, surface water isn’t available, can’t is forbidden to be used or the extraction of surface water is ecologically and energetically not worthwhile, then a cooling unit is set to use.

4.4. Compression cooling unit

4.4.1. Task of the cycle process demonstrated on the refrigerator

The task of the refrigerator is to keep its contents cooled to prolong the consumption period. Thus, it is an area that needs to be cooled. That is the task of the cooling unit. A compression cooling unit is used for the domestic refrigerator.

A refrigerant circulates through lines at a lower temperature and pressure in the area of the domestic refrigerator which needs cooling. Due to the difference in temperature between refrigerant and the stored food, a heat flux flows to the refrigerant which in turn evaporates due to this heat input. This evaporation steam is sucked into the compressor, where it is compressed and thus has a higher pressure as well as temperature. The refrigerant can now release the absorbed heat. It would normally be released into the ambient air via heat exchanger. The refrigerant now has to be brought back down to the cooler temperature and correspondingly lower pressure so to close the cycle. This process happens via throttle device or expansion valve.

This ongoing process is based on various physical laws. This is the reason why the key connections are mentioned again.
4.4.2. Physical principles

First principle
The first principle says that the sum of all energy in a closed system stays constant or even, respectively. With respect to the cooling unit, this means that in the cycle of the cooling unit neither produces thermal energy nor can thermal energy be destroyed. The only possibility is to transform the different forms of energy.

Second principle
The second principle says that thermal energy without external influences can only be transferred to a warmer object on to a colder object. The opposite direction, that is to say the heat transfer from a cold object to a warmer object, is only possible with the effort of external machines.

Changes in states of aggregation
Substances exist in the three states of aggregations solid, liquid and gaseous. The possible changes in the states of aggregation and their descriptions are illustrated in the following diagram.

![Changes in states of aggregation and their description](image)

The fact that energy is required to change a state of aggregation acts as a base for the cycle in the cooling unit. During this process of the change of state, the temperature of the substance stays constant. This trait is made visible with water as an exemplary substance in the following temperature-enthalpy diagram. The temperatures as well as the enthalpy values apply to 1 kg at standard conditions (atmospheric air pressure 1,013 mbar).

![Changes in state of aggregation of water with the relating temperatures and enthalpy values at standard conditions](image)
A-B: Heating of water

This line represents the heating of water. Here, the temperature (vertical axis) changes from 0 °C to 100 °C. The enthalpy (x-axis) has increased to 419 kJ/kg. The referential point, where the enthalpy is 0 kJ/kg, can be chosen at random. In this example, the referential point was chosen for liquid water at 0 °C. Subsequently the enthalpy difference between point A and point B is also 419 kJ/kg.

Conclusion: Energy of 419 kJ/kg is required to heat 1 kg of water from 0 °C up to 100 °C.

B-C: Evaporation of water

The line here shows the evaporation of water. It is visible on the vertical axis, that the temperature hasn’t changed during this process and stays at a constant 100 °C. Nevertheless, the enthalpy rises from 419 kJ/kg to 2,676 kJ/kg. The energy of 2,257 kJ/kg required for this process is exclusively applied to change the state of aggregation. The water vapor at point C is also referred to as saturated steam.

Conclusion: Energy of 2,257 kJ/kg is required to change 1 kg of water from a liquid state into a gaseous state.

C-D: Superheating of water vapor

This line represents the superheating of water vapor. Looking at the vertical axis, it is clear that the temperature rises again during this process. It rises from 100 °C to 115 °C. Here, the enthalpy also increases by 28.3 kJ/kg, from 2,676 kJ/kg to 2,704 kJ/kg.

Conclusion: Energy of 28.3 kJ/kg is required to heat 1 kg of water vapor from 100 °C to 115 °C.

All the processes are reversible. The difference is that instead of energy being required, it is released.
C-B: Condensation of water vapor

This line not only shows the temperature and enthalpy of evaporation but also that of the inverted process of condensation. The axis representing the temperature shows how it stays constant at 100 °C. The enthalpy, however, drops from 2,676 kJ/kg to 419 kJ/kg. Here an energy level of 2,257 kJ/kg is released.

Fig. 4-10  Heat of condensation at standard conditions

Conclusion: Energy of 2,257 kJ/kg is released at the transformation of 1 kg of water vapor at 100 °C into 1 kg liquid water of 100 °C.

This temperature-enthalpy diagram shows that the most energy is required/released during the processes, where the state of aggregation is changed. This change in enthalpy simultaneously represents the storage of thermal energy. This physical principle is applied in the refrigeration unit.

Boiling point or evaporation temperature

The boiling point or the evaporation temperature describes the temperature at which the relevant substance evaporates, meaning the changing the state from liquid to gaseous. These temperatures depend on the ambient pressure of the substance. In the example with water, the evaporation temperature is 100 °C at an ambient pressure of (1,013 mbar). The following graph demonstrates, with water as an example, how the evaporation depends on the ambient pressure.

Fig. 4-11  Evaporation temperature in dependence to ambient pressure

The graph demonstrates that a high boiling temperature has high pressure and a low boiling temperature low pressure. As mentioned above, the refrigerator takes advantage of the fact that changing states of aggregation requires or releases a lot of energy, depending on the kind of process. This energy is drawn from the cooling chamber in the example of the refrigerator. The temperatures in the refrigerator lie at about +5 °C. The previous diagram shows that the water would require an atmospheric pressure of 10 mbar (1,000 mbar beneath the atmospheric air pressure). This negative pressure (vacuum) is very hard to generate from a technical point of view.

As a conclusion, water acting as a heat carrier is not suitable in the cycle of the refrigeration unit. A medium that already evaporates at lower temperature is needed and refrigerants have this particular feature.
4.4.3. Refrigerant

Refrigerants describe the operating fluid circulating in the refrigeration unit. During the explanation of the basics of the refrigeration process, only water was mentioned and it truly possesses many of the features that are required for a refrigerant. Water is inexpensive, plentiful, non-toxic and possesses a great evaporation and liquefaction enthalpy.

Water is not suitable as a refrigerant for the compression cooling unit, because the pressures and temperatures at which changes in states of aggregation occur are inconvenient. In fact, the refrigerants used in these processes are more volatile than water, i.e. substances that evaporate at relatively low temperatures and technically well manageable pressures.

Requirements of refrigerants

Essentially, every substance could be used as a refrigerant, as long as it evaporates and liquefies at technically achievable pressures and the required temperatures. A refrigerant should also have a boiling point that is as low as possible and a small steam volume in atmospheric pressure. It is also can't attack the components and lubricants of the refrigeration unit. Additionally, it should be non-toxic, non-flammable and non-explosive.

Types of refrigerants

Chlorofluorocarbons (CFCs):
For decades, chlorofluorocarbons (CFCs) were used as a refrigerant. CFCs are harmful to the environment, because they break down the ozone layer and enforce the greenhouse effect. This and also because of their long retention time in the atmosphere is why they are so harmful. It also is the reason why they were gradually banned and are now not available anymore since the 1990s. It was replaced by hydro chlorofluorocarbons (HCFCs) and partly fluorinated hydrocarbons (HFCs) refrigerants.

Hydro chlorofluorocarbons (HCFCs):
HCFCs are hydro chlorofluorocarbons with a significantly shorter retention period. The potential for breaking down the ozone layer lies only at a fraction of that of the CFCs. They are still harmful to the climate and are meanwhile also forbidden little by little.
Thus, the new use of HCFCs is forbidden in the EU since 2010. From the year 2040 on, a worldwide prohibition should be in place (Montreal Convention).

Partly fluorinated hydrocarbons (HFCs):
The HFCs are chlorine-free. They don't break down the ozone layer but they do enforce the greenhouse effect.

Often used refrigerants

Nowadays, HFCs should be used as a minimum as a refrigerant. This includes the following refrigerants:
- R-134a
- R-152a
- R-32
- R-125
- R-23
- R-404A
- R-407C

Other substances which can be found like that in nature and thus are considered environmentally neutral. This includes:
- R-717 (ammonia NH₃)
- R-290 (propane CH₃CH₂C)
- R-744 (carbon dioxide CO₂)

Choosing a refrigerant depends on the area of application of the cooling unit.
4.4.4. Refrigeration cycle on the example of a domestic refrigerator

In the functional diagram of the refrigeration cycle, you can see that a closed piping system represents the refrigeration cycle itself. The refrigerant flows through the piping system. The refrigerant takes over the heat transport for the refrigeration cycle.

Fig. 4-12 Refrigeration cycle of a domestic refrigerator (sources: Siemens, Wikipedia)

A-B: Evaporation
A refrigerant possesses the characteristics to evaporate at a low temperature and at a certain pressure. In the domestic refrigerator, where a temperature of about +5 °C is strived for, the refrigerant already evaporates at the aforementioned temperature. The evaporation changes in the heat exchanger of the state of aggregation of liquid to gaseous. For these changes in state, energy is required which the evaporation heat exchanger gets from the environment. In the example of the domestic refrigeration, the environment is the actual cooling space itself. When the energy is withdrawn from the cooling space, the latter or the therein stored goods respectively cools down.

B-C: Compression
The now gaseous refrigerant is then compressed via compressor. As a result, the pressure and temperature of the refrigerant both increase. The temperature also increases because the engine waste heat of the compressor is transferred onto the refrigerant. Thus, the thermal capacity of the refrigerant additionally increases. The compression process requires energy.

C-D: Condensation
The refrigerant now circulates through a heat exchanger. The heat exchanger in the domestic refrigerator is mostly located on the backside of the refrigerator in the form of a grid. The hot and vaporous refrigerant thusly cools down because of the cooler ambient air. Due to the cooling process, the gaseous refrigerant condenses in the heat exchanger and becomes liquid again.
As a result, the complete energy of condensation as well as the energy of the engine waste heat is released. After the condensation, the refrigerant still is at a high pressure.

D-A: Expansion

The existing high pressure in the expansion valve rapidly diminishes so to reach the initial pressure again. This reduction in pressure requires energy which is taken from the still warm refrigerant. That is why the temperature of the refrigerant also drops to its initial temperature.

4.4.5. Components in a cooling unit

A cooling unit essentially consists of four components.

Evaporator

The evaporator is in a heat exchanger. The refrigerant circulates through the heat exchanger. The substance to be cooled is situated outside of the heat exchanger. Energy is extracted from the environment via heat exchanger which makes the refrigerant evaporate. The evaporator isn’t directly visible in the domestic refrigerant as the heat exchanger is situated in the wall of the domestic refrigerator in the form of small pipes. In an industrial refrigeration cell, the evaporator is often found together with a fan which makes the ambient air circulate in the heat exchanger.

Compressor

The compressor compresses the vaporous refrigerant. As a result, the temperature and pressure increase. The compressor in the compression cooling unit is powered by an electric motor. There are various compressors with different compression principles. For more information, see the chapter “Refrigeration” in the basic principle brochure. A hermetic compressor is normally used in the refrigerator. The motor and compressor are housed in a welded and tightly closed case and the refrigerant flowing through also cools the motor.
Condenser
The condenser also is a heat exchanger. The refrigerant circulates through the condenser, too, which also changes from a gaseous to a liquid state. The condensation heat is given off to an ambient medium. It is ambient air in the refrigerant. A freestanding piping grid is located on the backside of the refrigerator through which the refrigerant flows. The heated air then flows through an opening in the kitchen paneling above the refrigerator into the room. Coolers which give off condensation heat to ambient air are often found in larger refrigeration plants. These are then installed on the roof, for example.

![Condenser grid on a refrigerator (left) (source: Wikipedia) and dry-cooler (right) (source: CIAT)](image)

Expansion
After the condenser, the refrigerant is liquid again. It has an even higher pressure and temperature than needed for evaporation, though. When the pressure is reduced again, a part of the refrigerant evaporates again. The energy required for this process is taken from the refrigerant by means of the temperature of the still liquid refrigerant dropping.

Expansion valves are applied so to adapt the circulating refrigerant to the process requirements. These expansion valves are either mechanical, so-called thermostatic throttling valves or electronically driven and regulated expansion valves.

![Thermostatic expansion valve (source: Danfoss) Electronic expansion valve (source: Siemens)](image)
4.4.6. The h, log p-diagram

The thermodynamic process in a cooling unit is very complex. They can only be calculated with considerable effort. The h, log p-diagram serves as a tool for simplification. In the chapter 2.2.3, the different changes of state of aggregation are illustrated in a temperature enthalpy diagram. In refrigeration technology, the pressure enthalpy diagram is preferred over the temperature enthalpy diagram. These kinds of specific diagrams are available for every refrigerant used in practice.

![h, log p-diagram of R-404A with evaporation heat \( \Delta h \) (source: DTU, Denmark)](image)

The enthalpy h (thermal capacity) is illustrated with a linear scale on the horizontal (axis of ordinate). She represents how much heat in kJ per mass is contained in kg in a substance depending on the state. Significant in the process is the respective change in enthalpy or difference in enthalpy. The vertical line illustrates the lines with the same enthalpy.

The pressure p is illustrated on the vertical axis (x-axis) in bar. The pressure is shown with a logarithmic scale so that working usefully in the diagram is possible. The horizontal lines are the lines with the same pressure.

The area between both limit curves (\( \Delta h \)) represents the evaporation heat in kJ per mass in kg. The evaporation heat decreases with increasing pressure. Left from the limit curve, the refrigerant is liquid and to the right, it is vaporous. Inside of both limit curves, the refrigerant is in the area of partially saturated steam, which means that a part is already vaporous while the other is still liquid.

The lines which – depending on the refrigerant – run between the two limit curves and drop down to the right after the second limit curve indicate the same temperature, respectively. Depending on the refrigerant inside the both limit curves which run horizontally and after the second limit curve sloping downwards...
4.4.7. The cycle of the refrigerator in the h, log p-diagram

The cycle of the refrigerator is simplified in the h, log p-diagram. Temperature, pressure as well as enthalpy can be determined via diagram depending on the state.

A-B: Evaporation

The refrigerant evaporates at about 0 °C and a pressure of 6 bar. So, heat can flow from the cooling space to the refrigerant. The enthalpy increases in the process during the evaporation of 237 kJ/kg up to 367 kJ/kg. The saturated steam is then heated even more which is why its temperature increases to 6 °C and its enthalpy to 373 kJ/kg.

B-C: Compression

The refrigerant is compressed. The motor heat largely flows into the refrigerant. The temperature of the refrigerant rises to 39 °C. The pressure increases to 13.5 bar. The enthalpy after the compression is 394 kJ/kg.

C-D: Condensation

The circulating refrigerant is now warmed to 39 °C and circulates through a heat exchanger which is surrounded by ambient air. The temperature in the vaporous refrigerant drops to 28 °C in the process and the thermal energy can be given off to the ambient air. Then, the refrigerant liquefies at 28 °C. The entire condensation heat is given off to the environment. 156 kJ/kg of thermal energy is given off in total. The refrigerant is subsequently liquid but still has a pressure of 13.5 bar.

D-A: Expansion

The pressure is reduced from 13.5 bar to 6 bar via expansion valve. The energy for the pressure reduction is taken from the refrigerant which is why its temperature is reduced to 0 °C.
4.4.8. Energy efficiency ratio (EER)

The coefficient of performance of a refrigerator is nowadays called energy efficiency ratio (EER). Hereby, the benefit is compared to the effort. The coefficient of performance is all the better, the less the compressor needs to perform. Consequently, the coefficient of performance is higher when the difference in temperature between the evaporation temperature and condensation temperature is small.

\[ \varepsilon_{KM} = \text{EER} = \frac{\Phi_0}{P_{el}} \]

- \( \varepsilon_{KM} \) energy efficiency ratio of a refrigerator EER \([-]\)
- \( \Phi_0 \) refrigeration capacity at the evaporator [W]
- \( P_{el} \) electrical power at the compressor [W]

The energy share of the circulation pump is to be taken into account for the actual energy efficiency ratio. These are the energy shares which are required so to overcome the pressure drop on the secondary side of either the evaporation or the condensation. Furthermore, the energy share for the control device inside of the refrigeration unit needs to be considered.
4.5. Compression cooling unit as heat pump

4.5.1. Introduction

A heat pump has the same structure and components as the compression cooling unit. The only change is the use of the evaporation and condensation heat. The goal of a cooling unit is that the evaporation heat of the refrigerant is taken from a substance or a room. During this process, heat becomes waste product. The use of that heat, which is waste heat in a refrigerator, is strived for in a heat pump. The refrigerant needs to be evaporated first before it can be compressed and thus used. The thermal energy for the evaporation process can be taken for example from ambient air, soil or ground water, lake water or river water (see chapter 3.3.4).

![Heat pump cycle with different heat sources for evaporating the refrigerant](source: Siemens, Wikipedia)

The coefficient of performance of the heat pump is referred to as COP. Here, too, the benefit is compared to the effort, whereby the benefit of the heat pump is located on the warm side, i.e. the condensation side. As with the refrigerator, the COP in the heat pump is higher, the smaller the difference in temperature between source inlet temperature and heating outlet temperature is. The source inlet temperature is crucial for the evaporation temperature and the heating supply temperature is crucial for the condensation temperature in this refrigerant process.

\[
\varepsilon_{WP} = \frac{\Phi_c}{P_{el}}
\]

\(\varepsilon_{WP}\) coefficient of performance of the heat pump \(\text{COP \ [-]}\)

\(\Phi_c\) heat output at condenser \([\text{W}]\)

\(P_{el}\) electrical output at the compressor \([\text{W}]\)
The energy shares of the heat pump have to be observed to overcome the pressure drop in the evaporator and condenser on the secondary side. This is done to get the actual COP. Also, the energy share meant for the control devices inside the heat pump are to be taken into account.

**Minimum requirement for heat pumps according to EN 14511**

The seal of quality “heat pump Keymark” is based on the independent performance testing which are implemented according to the standards EN 14511 (part 1-4), EN 15879, EN 16147 and EN 12102. Furthermore, the standards of manufacturing conditions and quality control are adhered to. This seal is a product test mark effective europewide (autumn 2015 onwards).

The following minimum requirements are needed so to meet the standards of EN 14511:

- **Air/water** COP > 3.1 at (A2/W35)
- **Brine/water** COP > 4.3 at (B0/W35)
- **Water/water** COP > 5.1 at (W10/W35)

**Explanation:**

- **A** (ambient air) Source inlet temperature air [°C]
- **W** (water) Source outlet temperature water [°C]
  or radiator outlet temperature water Wasser [°C]
- **B** (brine) Source inlet temperature brine [°C]

Thus this means that the test point B0/W35 for example indicates that a brine/water heat pump is run with 0 °C source temperature and 25 °C water supply temperature.
4.6. Absorption and adsorption cooling unit

4.6.1. Introduction

Next to the compression cooling unit the following cooling units are used:

- Absorption cooling unit
- Adsorptions cooling unit

The refrigeration cycle of both types from condenser to expansion and evaporator are similar to that of the compression cooling unit. The essential difference can be found in the types of compressing the refrigerant.

Use

The decision to either employ a compression or absorption cooling unit or adsorption cooling unit respectively, is dependent on the available operating power. If for example a steam or a hot water boiler, which are only optimally used in winter, is available, then it makes the most sense to use its free capacity in summer to generate cold. This is done by linking the former with an absorption or adsorption cooling unit. The use of such a unit would also be optimal, if waste heat from a production process or a back pressure turbine is available. The absorption and adsorption cooling units are often installed in developing countries, where the power grid isn’t optimally developed yet. Compared to compression cooling units, these two types aren’t operated by electricity but heat. The absorption and adsorption units are used to cover the base load because they require a lot of time.

4.6.2. Absorption cooling unit

Absorption

An absorption process refers to the uptake of gas by a liquid or solid substance in the form of a physical bond. Here, the absorbing substance and the gas which is to be absorbed form a working fluid pair. However, absorption only takes place if working fluid pair is chemically compatible and only at a given pressure/temperature ratio, which differs for each working fluid pair. This process is also reversible, i.e., the absorbed gas can be desorbed again at a different pressure/temperature ratio. The evaporation pressure is very low (vacuum), which leads to a corresponding massive machine design.

Function

As with the compression cooling unit, the absorption cooling unit uses a refrigerant. This refrigerant also evaporates at a low pressure in the evaporator via supply of heat. This heat is taken from a substance, which cools the latter down. Then, the gaseous refrigerant is compressed at a higher temperature and pressure. The condensing heat in the condenser is released, before the refrigerant is brought to a low pressure in the expansion valve.

The function principle of the compressor in the absorption cooling unit, the compressor in the absorption cooling unit is not made up of a compressor but an absorber and an extractor. Moreover, the compression doesn’t take place in a compressor but via refrigerant cycle. The following two functions replace the compressor:

- The extraction process of the refrigerant vapor takes place by means of absorption. This is why the gaseous refrigerant flows into the absorber, because a liquid solvent absorbs it there.

- The compression and ejection of the compressed and hot refrigerant vapor is replaced through the process in the extractor in the absorption cooling unit. Here, the now liquid solvent, enriched with refrigerant, is transported from the absorber into the extractor. Heat from the outside is added to the solvent in the extractor. This increases the temperature and pressure of the solvent. The refrigerant evaporates out of the solvent again and is lead to the condenser in a gaseous state.
The mechanical compressor is thus exchanged with a solvent cycle. The latter is also referred to as the thermochemical compressor.

Refrigeration cycle in detail
The hot refrigerant vapor under higher pressure flows from the extractor in the solvent cycle into the condenser. There, it flows through the heat exchanger, gives off evaporation heat and condenses at the same time. The evaporation heat which is set free passed on to the heat exchanger cycle. The pressure of the still pressurized and now liquid refrigerant is lowered in the expansion valve. In the evaporator, heat exchanger in the evaporator then dispenses the refrigerant. The pressure in the evaporator is kept at such a low level, that the refrigerant already evaporates at very low temperatures. If the heat is drawn from a secondary medium in the heat exchanger and the secondary medium cools down, the refrigerant evaporates again. The resulting refrigerant vapor flows through the absorber.

Solvent cycle in detail
The solvent is sprayed in the absorber. The refrigerant vapor from the evaporator thus intensively comes into contact with the spray mist of the solvent and is absorbed in the process. The solvent reacts with the refrigerant. This chemical process also sets free reaction heat, which needs to be discharged. The heat exchanger takes over that task, where the same secondary medium circulates which later also absorbs the condensation heat of the refrigerant cycle and thus is preheated.
The refrigerant, which is now “diluted” with the solvent, is now pumped through the solvent pump and the temperature changeover, where the cold solvent is preheated from the absorber with the hot solvent from the extractor, into the extractor. The extractor is heated from the outside. This heat supply causes the refrigerant to evaporate and thus separate from the solvent and provides the needed increase in pressure and temperature. While the thus resulting refrigerant vapor flows into the condenser of the refrigerant cycle, the solvent is lead back into the absorber via temperature changeover. The solvent cycle starts over.

![Absorption cooling unit](source: Trane Roggenkamp)

**Difference in operating power**

Unlike the mechanical operating power needed for the compressor, the absorption cooling unit requires thermal power for its operating power. This can be in the form of vapor, hot water, warm water, a gas/oil boiler, etc. Mechanical power is only needed for the motor of the solvent pump.

**Possible working fluid pairs**

Know working fluid pairs which are often used in absorption cooling units:

- Water/lithium-bromide (water as refrigerant)
- Ammonia/water (ammonia as refrigerant)

Further working fluid pairs, which are often used in special facilities:

- Ammonia/lithium nitrate (ammonia as refrigerant)
- Methylamine/water (methylamine as refrigerant)
- Methanol/lithium-bromide (methanol as refrigerant)

**4.6.3. Adsorption cooling unit**

**Adsorption**

The adsorption process describes the absorption of gasses off of the surface of a solid substance. Thus, it is a physical process, where a gaseous substance sticks to the surface of a solid substance. This feature also depends on pressure and temperature. This process is reversible. The release of the gaseous substance from the surface is called desorption. This is why the substance is expelled again at a defined pressure and temperature ratio.

**Function**

The adsorption cooling unit also uses a refrigerant. This refrigerant evaporates at a lower pressure in the evaporator, too. Here, heat is withdrawn from the substance, which makes the latter cool down. Because of the adsorption, the gaseous refrigerant sticks to the surface of the porous adsorber (sorbent). During the adsorption process, heat is given off, which needs to be discharged. This happens with the help of a heat exchanger cycle. This phase of adsorption lasts until the sorbent is saturated and isn’t capable of absorbing refrigerant any longer. Subsequently, the desorption phase starts. Here, the now saturated sorbent is heated via externally supplied heat. The refrigerant evaporates again, the pressure and temperature rise.
The now released, vaporous refrigerant flows into the condenser. There, the refrigerant condenses again and gives off condensing heat onto the heat exchanger cycle. Both the temperature as well as the pressure of the refrigerant drop again and the refrigerant can evaporate again.

Fig. 4-24 Adsorption cycle (adsorbent 1 in desorption phase, adsorbent 2 in adsorption phase)

1 Evaporator 2 Adsorbent 1 3 Adsorbent 2 4 Condenser 5 Expansion valve
A Utility cycle refrigeration unit B Operating power cycle
C Heat exchanger cycle

Butterfly valves are used for directed transport of the refrigerant through the corresponding chambers. They open and close according to specific differential pressures. Two adsorbents are operated anticyclical so to continuously produce heat or cold, depending on the use. This means that an adsorbent is located in the adsorption process while the other carries out the desorption process.
Difference in operating power

Instead of using mechanical operating power for the compressor, the adsorption cooling unit also uses thermal energy as operating power. This thermal energy is taken from vapor, hot water, warm water, gas/oil boilers etc.

Possible refrigerant sorbents

The known combinations which are often used in adsorption cooling units:

- Water/silica-gel (water as refrigerant)
- Water/zeolith (water as refrigerant)
- Water/activated-carbon (water as refrigerant)

When water is used as a refrigerant, the evaporation temperature is restricted to a minimum of 5…6 °C as water would otherwise freeze. A suitable refrigerant needs to be used at lower temperatures than that.

Primary substances that are porous and thus possess a greater surface are well suited as a sorbent.
5  Hydronics in building technology

5.1.  Introduction

Heating, ventilation and air conditioning (HVAC) plants are used to create comfortable environmental conditions for human beings.

To satisfy this requirement in our climatic zone, heat – but also cooling energy – must be generated, adequately regulated and delivered to the right place at the right time.

Hydronic systems are designed to integrate the required plant components in the circuit between the heating / cooling source and the consumer in a way that optimum operating conditions can be reached for the:

- heating / cooling source (temperature, flow of water)
- transportation of the heating / cooling energy carrier such as water or steam
- integrated control equipment

This documentation entails the most important information from the learning modules of the training program “Hydronics in building technology”. The diagrams shown are largely taken from the training program. Many of these diagrams are animated and interactive in the training program. This means you can try out how the circuits and components behave under different conditions.

Ordering training program

If you are interested in the training program “Hydronics in building technology”, please contact your Siemens sales office.

Fig. 5-1  Start screen of the self-learning “Hydronics in building technology”
5.2. **Key components of a hydronic plant**

**Fig. 5-2** Key components of a hydronic plant

- Controller (with sensor)
- Actuator
- Controlling element (three-port valve)
- Heating boiler (heat generation)
- Radiator (heat consumer)
- Circulating pump
- Feed lines
- Balancing throttle
- Return pipes

**Fig. 5-3** Circulation in a hydronic plant

Valve closed

Valve open
5.3. Representation of hydronic circuits

The hydronic circuits shown so far are easy to understand for many people. For the expert, however, they are not common practice because they are not suited to explain plant-related interrelationships. For this reason, schematic diagrams are used in the HVAC field. All the essential elements of an HVAC plant can be shown there and technical processes and interrelationships are easier to understand.

![Pictorial diagram of a plant](image1)

**Fig. 5-4** From the pictorial to the schematic plant diagram

There are two different kinds of schematic plant diagrams:

- geographic diagram
- synoptic diagram

![Geographic diagram](image2)

**Fig. 5-5** Geographic and synoptic diagram of a basic plant
**Geographic diagram**

Often, the schematic diagram shown above is used for basic plants. It is called a geographic diagram and is closely related to the actual design of the plant.

![Geographic diagram](image)

Fig. 5-6 Example of a heating plant with several consumers in geographic diagram

The geographic diagram is less suited for larger plants, because it becomes more and more difficult to understand, especially when interrelationships between consumers and heating / cooling sources are getting complex. For example, as in the case of a ground water heat pump with storage tank and additional heating boiler that delivers heat to several distributed consumers.

For this reason and due to the extensive use of CAD systems, the kind of diagram frequently used today is a more structured one.

**Synoptic diagram**

The synoptic diagram shows the schematic representation of complex and extensive hydronic plants which are easy to understand and in a clearly structured manner.

With the synoptic diagram, a number of important rules are typically considered:

- The supply line is shown at the top, the return at the bottom.
- Generators and consumers are shown parallel in the direction of flow between supply and return lines

**Note on the representation of controlling elements**

In the schematic diagrams of hydronic circuits, it is also important that the correct symbols of the plant components are used.

Especially important is the correct use of the symbol for the three-port controlling element (stroke or slipper valve).

The two triangles representing the ports with variable flow are filled in while the triangle representing the port with constant flow is empty, as shown below.

![Synoptic diagram](image)

Fig. 5-7 Schematic representation of the valve ports

Filled variable flow

Empty constant flow
In many schematic diagrams used in the training program “Hydronics in building technology” as in this document, controlling elements are shown without their actuators. Thus the diagrams are easier to understand. In addition, the assumption is made that the controlling element is always a valve.

Examples of geographic and synoptic diagrams:

Geographic diagrams

Synoptic diagrams

Fig. 5-8  Example of geographic and synoptic diagrams
5.4. Consumer with basic hydronic circuits

5.4.1. Circuits with variable and constant flow

The output (quantity of heat/cold) of a generator or consumer is proportional to the product of mass flow and temperature difference across the generator or consumer.

\[ \dot{Q} = \dot{V} \cdot \Delta T \cdot c \cdot \rho \]

For our considerations and for the standard applications in building technology, we consider the density \( \rho \) and the specific heat capacity \( c \) to be constant. This means that the output of a generator or consumer is proportional to the product of volume flow and temperature difference.

\[ \dot{Q} = \dot{V} \cdot \Delta T \]

Hence, in hydronic circuits, the following variables can be used for adjusting the output:

- Volume flow is changed (temperature stays constant)  
  \( \Rightarrow \) Variable-flow operation  
  \( \Rightarrow \) Flow rate control

- Temperature is changed (volume flow stays constant)  
  \( \Rightarrow \) Variable-flow operation  
  \( \Rightarrow \) Mixed control
5.4.2. Flow rate control and mixed control

There are two hydronic circuits for flow rate control (variable flow) and mixed control (constant flow), respectively.

**Flow rate control**
The following two circuits are used in the flow rate control (variable flow circuits):

- Throttling circuit
- Diverting circuit

Both hydronic circuits adjust their outputs by varying the volumetric flow passing through the consumer. They require a proceeding pump that supports the volume flow in the consumer.

**Mixed control**
In the mixed control (constant flow), the following circuits are used:

- Dual admixture circuit (and dual admixture circuit with fixed pre-mixing)
- Injection circuit (with a 2-way or global valve)

Both admixing circuits adjust their output by delivering different inlet temperatures into the consumer. They contain their own pump that transports the volume flow through the consumer.
5.5. Basic hydronic circuits

5.5.1. Throttling circuit

**Mode of operation**
When the valve is adjusted, the volumetric flow will change both in the heating / cooling source section and in the consumer section of the hydronic circuit. As a result, pressure conditions will vary considerably throughout the system.

**Characteristics**
- Low return temperatures in part load operation
- Variable volumetric flow throughout the entire plant
- On startup, the correct fluid temperature will reach the consumer with a certain delay (dead time, depending on the length of the pipe and the cooling down effect)
- When the valve is fully closed, the pump can reach excessive temperatures (⇒ use of speed-controlled pumps)

**Field of use**
- Air heating coils where there is no risk of freezing
- Air cooling coils with dehumidification
- Hot water storage tank charging
- District heat connections (direct or with heat exchanger)
- Storage tank charging and discharging
- Plants using condensing boilers

**Types of diagrams**

- Geographic diagram
- Synoptic diagram
5.5.2. **Injection circuit with two-port valve**

**Mode of operation**

The pump in the heating source circuit injects more or less hot supply water into the consumer circuit, depending on the position of the two-port valve.

As a result, there is a constant volumetric flow with varying temperatures in the consumer circuit.

In the heating source circuit, by contrast, the volumetric flow and pressure vary significantly, a fact to be taken into consideration in the case of plants with several consumer circuits.

### Characteristics

- Relatively low return temperatures
  (cold … consumer return temperature at 100 % load)
- Even temperature distribution across the heat consumer
- Constant volumetric flow in the consumer circuit
- Variable volumetric flow in the source circuit
- Small risk of freezing with air heating coils
- With a fully closed valve, the pump in the heating source circuit can reach excessive temperatures (⇒ use of speed-controlled pumps)

### Field of use

- Heat storage tanks and heat pumps
- Low temperature boiler plants (condensing boilers)
- Direct district heat connections
- Not suited for air cooling coils with dehumidification control
- Radiators and floor heating

### Types of diagrams

- **Geographic diagram**
- **Synoptic diagram**
5.5.3. Mixing circuit

Mode of operation
A three-port valve subdivides the hydronic circuit into a primary circuit (heating source circuit) and a secondary circuit (consumer circuit). The hot water delivered by the heat source and the cooler return water are mixed to attain the supply temperature required for the consumer, thereby adjusting the output to meet the demand for heat.

![Valve fully closed](image1)
![Valve fully open](image2)

E.g., mixing circuit in a room heating group

Characteristics
- Heating: low return temperatures with small loads
  - Cooling: high return temperatures with small loads
- Variable volumetric flow through the heat source circuit
- Constant volumetric flow with variable temperatures through the consumer circuit
- Even temperature distribution across the heat consumer
- Low risk of freezing with air heating coils

The mixing circuit is not suited for plants with a distance of more than 20 m between bypass and control sensor. The long transportation time (dead time) makes the control task much more difficult.

Field of use
- Control of radiator systems
- Air heating coils where there is a risk of freezing
- Plants with low temperature heat sources or heat pumps

Types of diagrams

- Geographic diagram
- Synoptic diagram

Mixing circuit
5.5.3.1.  Mixing circuit with fixed premixing

Here too, a three-port valve subdivides the hydronic circuit into a primary circuit (heat source circuit) and a secondary circuit (consumer circuit). Fixed premixing ensures that a certain portion of cooler return water will always be added to the supply flow. This is applicable when, under design conditions, the required supply temperature to the consumer is considerably lower than the supply temperature delivered by the heating producer. Thus, it is made certain that the three-port valve will operate across its entire valve stroke (from the fully closed to the fully open position).

![Valve fully closed](image1)

Valve fully closed  ![Valve fully open](image2)

Valve fully open

Mixing circuit with fixed premixing, example: Room heating group with floor heating

**Characteristics**

- Generally low return temperatures
- Variable volumetric flow through the heat source circuit
- Constant volumetric flow with variable temperatures through the consumer circuit
- Control across full valve stroke

The mixing circuit with fixed premixing is not suited for plants with a distance of more than 20 m between bypass and control sensor. The long transportation time (dead time) makes the control task much more difficult.

**Field of use**

- Consumer circuits where the flow temperature is lower than that of the heat source circuit
- Control of floor and radiator heating systems with high temperature heat sources (e.g. wood burning boilers)

**Types of diagrams**

![Geographic diagram](image3)

Geographic diagram  ![Synoptic diagram](image4)

Synoptic diagram

Mixing circuit with fixed premixing
5.5.4. Diverting circuit

Mode of operation
The valve distributes the supply flow over the consumer and the bypass. Depending on the position of the valve, more or less water flows through the consumer. The output of the consumer is controlled by adjusting the volumetric flow.

When the valve is fully closed, the temperatures of supply and return are approximately equal.

E.g., diverting circuit in a cooling system

Characteristics
- Changes to the volumetric flow varies thermal output at the consumer
- Variable volumetric flow through the consumer circuit
- Constant volumetric flow and pressure in the heat / cooling source circuit (advantageous in plants with several zones)
- Medium to high temperatures in return to the heating / cooling source
- On startup, the boiler supply temperature reaches the heat consumer with only little delay (provided that the controlling element is rather close to the consumer)

Field of use
- Air cooling coils with dehumidification
- Air heating coils where there is no risk of freezing
- Heat recovery systems
- Hot water heating
- Not suited for plants with a district heat connection (high return temperatures)

Types of diagrams

Diverting circuit
5.5.5. **Injection circuit with three-port valve**

**Mode of operation**

The pump on the lower left produces the pressure required in the heating source circuit, including the pressure drop across the valve. The pump above produces the pressure in the consumer circuit. The pump in the heat source circuit injects more or less hot supply water into the consumer circuit, depending on the position of the three-port valve. The hot water mixes with cooler return water from the consumer which the consumer’s pump sucks in via the bypass. As a result, there is a constant volumetric flow with varying temperatures in the consumer circuit.

![Injection circuit with three-port valve](image)

- **Valve fully closed**
- **Valve fully open**

**Characteristics**

- Constant volumetric flow in both the heat source and the consumer circuit
- Variable volumetric flow through the bypass
- Relatively high return temperatures (corresponding to the heating source supply temperature when load = 0 %, and the consumer return temperature when load = 100 %)
- Even temperature distribution across the heat consumer
- Small risk of freezing with air heating coils

**Field of use**

- Radiator and floor heating systems
- Air heating coils where there is a risk of freezing
- Air cooling coils without controlled dehumidification
- Hot water storage tank charging
- Not suited for plants with district heat connection (high return temperatures)

**Types of diagrams**

![Geographic diagram](image)

- Geographic diagram

![Synoptic diagram](image)

- Synoptic diagram
5.6. Distribution circuit

In practice, one generator mostly supplies multiple consumers. The distribution circuit is the link between the generator and multiple consumers. It distributes the generator supply to various consumer circuits, collects the medium from all consumer circuits collected and returns it to the generator.

![Distribution circuit as connecting element between generator side and consumer side](image)

**Requirements**

The consumer side and generator side place certain requirements on distribution circuits e.g. pressure conditions, constant or variable flow-through quantity, and required feed and return temperatures, etc.

⇒ Various types of distribution circuits are needed to meet all these requirements.

**Suitable combinations**

The distribution circuit can’t be observed on its own. It is important to use the generator and consumer circuits suitable for the distribution type. From the distributor circuit’s point of view, all the properties listed above must be the same (or similar) for all connected consumers.

Therefore we will consider the distributor circuit in regards to overall hydronic setups.

![Model of a hydronic circuit](image)
5.6.1. Combinations of distributor and consumer circuits

The overview includes a number of possible generators and consumers (list not conclusive). Not all generators can be combined with every consumer, though.

We will focus on three types of distributor types and suitable and appropriate consumer circuits that can be combined with selected generators and consumers so to provide efficient solutions. The solutions vary in regard to energy efficiency.

Generation – Distribution – Consumption / Delivery (Emission)

![Diagram showing combinations of generator, distributor, and consumer circuits.]

Fig. 5-13 Overview generator, distributor and consumer

* should be avoided; not energy-efficient from the view-point of the main pump
5.6.2. Low-pressure distribution

Valve closed
Valve fully open

Distribution between wood-fired boiler and room heating group

Characteristics

- High return temperature to generation
- Constant volume flow in generation
- Clear hydronic separation between generation and consumer

Important for trouble-free use

- Generously size distribution and above all the bypass (short circuit)
- Connected consumer groups with constant or year round heat demand at the start of distribution (prevent unneeded flow through distribution)

Field of use

- Generation requiring a high return temperature e.g.,

Energy efficiency

There is only limited energy efficiency in this combination of distribution and consumer circuits.

Reasons:

- Volumetric flow drawn by the distribution from the generation is constant and runs with high temperature. The temperature differential between distribution supply and return is very low at zero load and small at partial load. This results in significant losses of thermal energy in the generation and distribution.
- The volumetric flow provided continuously by the distribution pump is only needed at full load. The loss of pump energy is also significant.
5.6.3. Pressure-less distribution

Distribution between wood-fired boiler and room heating group

Characteristics
- High return temperature to generation
- Constant volume flow in generation
- Clear hydronic separation between generation and consumer

Important for trouble-free use
- Generously size distribution and above all the bypass (short circuit)
- Connected consumer groups with constant or year round heat demand at the start of distribution (prevent unneeded flow through distribution)
- Consumers with a demand for high supply temperatures (e.g. heating coils in air handling units or domestic hot water heat exchangers) should be connected before the bypass, i.e. on the generation side of the distribution

Field of use
- Generation requiring a high return temperature (e.g. wood burning boilers)

Energy efficiency
There is only limited energy efficiency in this combination of distribution and consumer circuits.
Reasons:
- Volumetric flow drawn by the distribution from the generation is constant and runs with high temperature. The temperature differential between distribution supply and return is very low at zero load and small at partial load. This results in significant losses of thermal energy in the generation and distribution.
- The volumetric flow provided continuously by the distribution pump is only needed at full load. The loss of pump energy is also significant.
5.6.4. Pressurized distribution at variable flow

Pressurized distribution at variable flow, e.g., cold water storage tank, cooling coil and chilled ceilings

Characteristics

- Cooling: High return temperature to generation
- Heating: Low return temperature to generation
- Variable volumetric flow in distribution

Important for trouble-free operation

- Controlling elements (valves) for the consumer circuits must be properly sized
- Variable speed control pump or adjustable bypass for minimum circulation
  (The variable speed control reduces the use of energy or shuts down at zero low to prevent damage to the pump. The bypass is mounted at the beginning of the distribution.)

Field of use

- Chilled water supply for cooling coils and chilled ceilings (example).
  (consider different working temperatures)
- Supply in district heating network (e.g. community heating supply)

Energy efficiency

This combination of distribution and consumer circuits is highly energy efficient.
It represents a future-oriented approach!

Reasons:

- The volumetric flow in the distribution is variable. It corresponds to the sum of all variable volume flows from all connected consumer circuits. As a result, the distribution only draws as much medium from the storage tank as is actually needed by the consumers.
- The temperature differential between distribution supply and return is sufficiently high at nominal load and increases with decreasing load (corresponding to return temperatures from variable volume consumer circuits). The temperature differential built up by generation (thermal energy) in the storage tank remains quite high and is used by this hydronic circuit in an energy-efficient manner.
5.6.5. Pressurized distribution at constant flow

Characteristics
- High return temperature to generation
- Constant volumetric flow in generation
- Primary pump must assume pressure loss across consumers when using diverting circuits
- Hydronic balancing is a challenge

Important for trouble-free use
- Correctly sized controlling elements (valves) for the consumer groups
- Only recommended, if with regard to pump output, key consumers can be operated without a group pump
- Generation must be suitable for high return temperatures

Field of use
- Generation requiring return minimum limitation
- At the risk of freezing, the air preheater (left) needs to be filled quickly with high media temperature.

Energy efficiency
The level of energy efficiency is unsatisfactory in this combination of distribution and consumer circuits.
Reasons:
- Nominal flow runs continuously throughout distribution as well as inlet and outlet of all consumer circuits. The temperature differential between distribution supply and return is very low at zero load and small at partial load. This results in considerable losses in thermal energy in the generation, distribution and connecting lines to consumer circuits.
- Distribution pump must be operated continuously at nominal flow. The required additional expense in pump transport energy is also considerable.
5.7. Controlling element

5.7.1. Types of controlling elements

The task of the controlling element is to control the volume flow between the generator and consumer in such a way that the heat output changes between 0 and 100 %. Every controlling element has a throttling port that can be more or less open – or also just open or closed. Taps (rotary movement) or valves (lifting movement) are used as controlling elements. The seat valves are divided into:

- Global valves
- 3-port valves

The combination of controlling element and actuator is often referred to as an actuating device.

Two port valve

The flow cross-section in the two port valve is decreased or increased through change of stroke. This results in a variable-flow volume flow.

![Diagram of Two port valve](Fig. 5-14 Two port valve)

3-port valve

The 3-port valve has a constant-flow valve port. Depending on whether the valve is installed as a mixing or diverting valve, the result in the change of stroke varies.

Mixing:
The exiting volume flow remains constant. It is a mixture of two variable flows.

Diverting:
The constant inlet volume flow is divided into two variable outlet flows.
(Note: not all types of 3-port valves are suited for the installation as diverting valves).

![Diagram of 3-port valve](Fig. 5-15 Three port valve)
Designation of ports
Ports can be designated differently, e.g. I, II, III (see illustration above) or AB, A, B.
Important qualities in designing valves are:
- necessary flow-through
- pressure drop across variable-flow line

5.7.2. Flow-through characteristics $k_V$- and $k_{VS}$

$k_V$-value: Flow-through characteristic value at certain stroke
The $k_V$ value corresponds with the flow-through of water through a valve at a constant pressure difference of 1 bar across the throttling port. The unit is $m^3/h$ or also l/min.
The $k_V$ value of a valve is dependent on the valve setting (stroke).

$k_{VS}$-value: Flow-through characteristic value when valve is open
The $k_V$ value, which ensues when the valve is open (nominal stroke $H_{100}$), is called the $k_{VS}$-value.
The manufacturers of valves and throttling elements specify these design-dependent variables $k_{VS}$ for every type of controlling element.
So to compare different makes and types, all valves are specified in a uniform manner:
- $k_V$ values relative to the $k_{VS}$-value: $k_V / k_{VS} = 0...1$
- Stroke $H$ relative to the nominal stroke $H_{100}$: $H / H_{100} = 0...1$

If $k_V / k_{VS}$ is shown as a function of the stroke range $0 ... 1$, then this is referred to as the valve characteristic curve (or basic valve characteristic curve).

![Fig. 5-16 Typical valve characteristic curve](image_url)
5.7.3. Rangeability $S_V$ and smallest controllable flow-through $k_{Vr}$

The rangeability $S_V$ is determined by the ratio of the nominal flow-through $k_{VS}$ to the smallest controllable flow-through $k_{Vr}$.

Rangeability $S_V = \frac{k_{VS}}{k_{Vr}}$

Typical values of rangeability are $50 \ldots 150$.

The rangeability is an important characteristic, used to assess the controllable range of a controlling element and is mainly dependent on the design of the valve plug and valve.

Smallest controllable flow-through $k_{Vr}$

The smallest controllable flow-through $k_{Vr}$ is the volume flow at the opening spring (where the gradient of the valve characteristic curve suddenly drops sharply).

It is either illustrated in relation to $k_{VS}$ ($k_{Vr}/k_{VS}$) or in $\text{m}^3/\text{h}$.

![Diagram](Fig. 5-17 Smallest controllable flow-through $k_{Vr}$ of a valve)

The operation of continuous control below $k_{Vr}$ is problematic because the controlling element only doses flow surges (open / closed).

5.7.4. Valve characteristic curves

A distinction is made between:

- Basic characteristic curve
  - mathematically determined, therefore theoretically
- Basic characteristic curve
  - Flow-through under norm conditions (1 bar, 25 °C), measured for each valve position

The most common basic characteristic curves are described as follows:

**linear**

Equal change in stroke leads to equal change of the $k_V$ value.

**equal-percentage**

A certain change of stroke produces a proportionally even change of the respective $k_V$-value, i.e. the greater the stroke (the more open the valve) the greater the impact of the stroke change on the flow-through. The characteristic curve is still flat in the lower stroke range. The higher up in the stroke range, the steeper it becomes.

**equal-percentage/linear**

A basic characteristic curve that is linear in the lower stroke range and then turns equal-percentage at about 30 % stroke onward.
The basic characteristic curve represents the basis for designing the valve plug which then determines the valve’s basic characteristic curve.

Equal-percentage

Equal-percentage/linear (0…30%)

Fig. 5-18 Comparing valve characteristic curves
5.8. Characteristic curve of the controlled system

When a valve is installed in a plant, the valve characteristic should compensate the heat exchanger characteristic curve. The resulting output of the heat exchanger can also be shown in the form of a graph, the so-called characteristic curve of the controlled system (also referred to as the control characteristic curve).

Here a linear valve characteristic was chosen, which does not provide for a good linearization of the resulting characteristic of the controlled system (heat exchanger / valve combination).
Here, the suitable valve characteristic curve (equal-percentage) was chosen. The resulting characteristic curve of a controlled system is almost linear. The controlled system can be controlled well.
6 Ventilation and air conditioning plants

6.1. Tasks of ventilation and air conditioning plants

Ventilation and air conditioning plants have the task to influence indoor air quality and thermal conditions as well as the humidity in the room in such a way that preset specifications are fulfilled.

6.2. Overview of ventilation and air conditioning plants (Classification according to EN 13779)

<table>
<thead>
<tr>
<th>Category</th>
<th>Thermodynamic functions</th>
<th>Plant description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Venti-</td>
<td>Heating</td>
</tr>
<tr>
<td></td>
<td>lation</td>
<td></td>
</tr>
<tr>
<td>THM-C0</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>THM-C1</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>THM-C2</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>THM-C3</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>THM-C4</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>THM-C5</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

x is controlled in the partial air conditioning plant.
(x) is influenced but not controlled in the partial air conditioning plant.

6.3. Definition of terms (according to EN 13779)

6.3.1. Plants

Ventilation plant
Plant with no or just one thermodynamic function (e.g. heating)

Partial air conditioning plant
Plant used to keep either the indoor air temperature or humidity at a desired value (heating/cooling or humidification/dehumidification), whatever the load status. If a plant is only capable of, for example, maintaining the temperature at a desired value through heating or cooling, while humidifying the air (but not to dehumidifying it), is by definition, still referred to as a partial air conditioning plant.

Complete air conditioning plant
Plant used to keep both the indoor air temperature and humidity at a desired value (through heating/cooling and humidification/dehumidification) at any load state.
Low-speed unit
Low-speed unit with flow speeds of < 10 m/s in the ducts (previous designation: low-pressure plant).
Mostly comfort air conditioning plants (e.g. office buildings, schools,...) with large volumes of air and relatively short distances. Air outlets can be installed directly into the ducts.

High speed unit
High speed unit with flow velocity in the air supply duct > 10 m/s (previous designation: high-pressure plant).
Mostly comfort air conditioning plants with smaller volumes of air and relatively long distances. Air diffusers can’t be installed directly into the ducts, as the air velocity first has to be reduced from high to low speed.

6.3.2. Air flows
The abbreviation for different air flows are taken from EN 13779.

Outdoor air (ODA)
Untreated air which flows into the plant from the outside or via opening

Supply air (SUP)
Air flow which enters into the treated room or air, which enters into the plant, after it was treated

Indoor Air (IDA)
Air in treated room or area

Extract Air (ETA)
Air flow which leaves the treated room or area

Recirculated Air (RCA)
Extract air which is lead back into the air handling plant and recycled das supply air.

Exhaust Air (EHA)
Air flow which flows back outside.

Symbols of individual plants and further information are listed in the Siemens document “Graphic symbols”.

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6.4. Aerotechnical plant elements

6.4.1. Distinction
This section describes the most important aerotechnical plant elements. It is only a brief overview without detailed information about the sizing and the specific individual criteria. The information concerning their use relating to control functions are explained in the documentation “BT_0096_EN Control of ventilation and air conditioning plants”.

Fig. 6-1 Schematic diagram of an air conditioning plant with plant elements and denotation of air flows

ODA outdoor air ETA extract air
SUP supply air RCA recirculated air
IDA indoor air EHA exhaust air

6.4.2. Weather protection grid
Weather protection grids for outside air and exhaust air keep rain and small animals (e.g. mice or birds) out of air ducts. They are often designed attractively as part of the building façade. In certain locations or situations, weather protection grids have to be heated, as they may otherwise freeze shut relatively quickly.

Fig. 6-2 Weather protection grid
6.4.3. Dampers

Function
A distinction is made depending on their function:

- Butterfly damper
- Throttle damper

Butterfly dampers close the duct cross-section via actuator motor, when the plant is turned off or in case of maintenance, repair work or failure. Depending on the demands, the butterfly dampers also have to be air-tight or even gas-proof.

With throttle dampers it is important to note that a proper throttle effect only takes place when the resistance of the open damper makes up a certain part of the total resistance in the duct system.

Designs
The dampers are available in a round and rectangle design.

Round dampers

Fig. 6-3  Butterfly damper/throttle damper in a round air duct (source: Trox)

In round ducts, normal throttle or butterfly dampers are made up of a round damper leaf which is installed on a rotary axis with a round or a square cross section.

Rectangle dampers

Fig. 6-4  Louver damper, working in opposite direction with gear mechanism

Rectangle dampers (so-called louver dampers) are normally made up of multiple lamellae, which can either be opened/closed concurrently or inversely. Depending on the control technological requirements, both options can be used. Almost exclusively the cost-effective concurrent damper is used as a throttle damper.
**Special designs**

Safety and fire dampers

![Fig. 6-5 Fire damper](image)

Safety and fire dampers are used to quickly close and seal the air ducts in case of emergency. They are not to be used for control functions other than safety related ones.

### 6.4.4. Air filter

**Function**

Air filters are machines and components of air handling units which filter particulate and gaseous impurities from the air and eliminate them.

Natural air shows contamination at a concentration between 0.05 and 3.0 mg/m$^3$. From an industrial point of view, the air filters are efficiently used at a concentration of about 20 mg/m$^3$.

![Fig. 6-6 Typical filter for ventilation and air conditioning plants](image)

**Classification based on filter classes**

Based on the test methods described in EN 779 and EN 1822, air filters are divided into the following three main categories:

- Coarse air filter
  - filter classes G1...G4
- Fine dust filters
  - filter classes F5...F9
- Aerosol filters
  - filter classes EU10...EU12
Owing to the increasingly stringent requirements in clean-rooms, the number of filter classes for aerosol filters has been extended (EU13…EU17) to satisfy the most stringent of specifications. The reduction of efficiency and efficiency rate of the filter depend almost entirely on the filter medium, while the dust storage capacity depends on both the filter medium and the filter's surface.

HEPA- and ULPA filters
Filter classes EU 10 to EU 14 are also known as HEPA filters (High Efficiency Particulate Air). Filter classes EU 15 to EU 17 are also known as ULPA filters (Ultra Low Penetration Air).

<table>
<thead>
<tr>
<th>Filter class</th>
<th>Characteristics (filtered particles, examples)</th>
<th>Classification EN 779</th>
<th>Advice for use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse air filter for particles &gt; 10 μm</td>
<td>Insects Textile fibers and hair Sand Fly ash Pollen Spores Cement dust</td>
<td>G1 G2 G3 G4</td>
<td>Simple application (e.g. as protection from insects in compact unit)</td>
</tr>
<tr>
<td>Fine dust filter for particles 1,0 - 10 μm</td>
<td>Pollen Spores Sand Cement dust Particles that cause stains or dust precipitation Bacteria and germs on host particles</td>
<td>M5 M6 F7</td>
<td>Pre-air and recirculation filter for civil defense installation, exhaust air spray booth, kitchen exhaust air, etc. Protection from pollution for air handling and compact units (e.g. window-type air conditioning, ventilators)</td>
</tr>
<tr>
<td>Aerosol filters for particles 0,1 - 1 μm</td>
<td>Germs, bacteria, viruses Tobacco smoke Metal oxide smoke</td>
<td>E10 E11 E12</td>
<td>Final filter for rooms with high and the highest demands (e.g. laboratory, production spaces in food, pharma, precision, optical, electronic as well as medical industries) Final filter for clean rooms of the classification 100,000, respectively. 10,000 Final filter for clean rooms of the classification 100,000, resp. 10,000 final filters for civil defense installations, exhaust air filters for nuclear plants</td>
</tr>
<tr>
<td>Aerosols</td>
<td>H14 U15 U16 U17</td>
<td></td>
<td>Final filters for clean rooms of the classification 10 - 1</td>
</tr>
</tbody>
</table>
Pressure differences in air filter

Initial pressure difference

The typical pressure differences in new air filters lie at:

- Coarse air filters in the range of 30...50 Pa
- Fine dust filters in the range of 50...150 Pa
- Aerosol filters in the range of 100...250 Pa

The filters are normally run with a speed of 2 – 3 m/s (depending on the filter surface).

End pressure difference

The recommended (and achievable) end pressure difference lies at:

- Coarse air filter in the range of 200...300 Pa
- Fine dust filters in the range of 300...500 Pa
- Aerosol filters in the range of 1,000...1,500 Pa

Increasing pressure difference during operation

During operation, the pressure difference in the filter increases due to deposit of dust. In the coarse air filters, for example, the increase happens by the square, in aerosol filters linear. The different developments of the increase in pressure allows for variations in the design of filters. Thereby, the contributing factors namely investment, energy, operation and maintenance costs are rated differently, depending on the situation in the system.

Normal operating time

The air filters are to be exchanged at the latest when the permitted end pressure difference (see above) is reached or at technical and/or hygienic dysfunctions. The air filter of the first filter level is to be exchanged at the latest after a year, those of the other filter levels (exception aerosol filters) after two years.
Filter types
The filter types are very versatile. There are various names being used, depending on material, installation mode, use, filter class and other factors.

Following are an exemplary selection of possible names for filter types.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Metal filters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>· Oil bath filters</td>
</tr>
<tr>
<td></td>
<td>Fiber filter</td>
</tr>
<tr>
<td></td>
<td>· Electric fiber filter</td>
</tr>
<tr>
<td></td>
<td>Activated carbon filter</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Installation mode</th>
<th>Vertical filter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>· Wall-mounted filter</td>
</tr>
<tr>
<td></td>
<td>· Ceiling-mounted filter</td>
</tr>
<tr>
<td></td>
<td>Duct filters</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Use</th>
<th>Disposable filter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Permanent filter (regenerative)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Filter class</th>
<th>see Fig. 6-7</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Air filter classification according to EN 779</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type of operation</th>
<th>Stationary filter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Automatic filter</td>
</tr>
<tr>
<td></td>
<td>Circulation filter, belt filter, automatic roll filter</td>
</tr>
<tr>
<td></td>
<td>Electric filter</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type</th>
<th>Diagonal flow filter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>· Drum filter</td>
</tr>
<tr>
<td></td>
<td>· Cylindrical filter</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Round air filter</th>
<th>· Pocket filter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>· V-shaped filter</td>
</tr>
</tbody>
</table>

Fig. 6-8  Possible names for air filter (source: Recknagel)

Fiber filter
The filter medium of the varying construction forms of these filters is fleece which is made from fibers from different materials such as glass, synthetic, natural products or metals. The general basic demands are long operating hours and low pressure differences. This is implemented by housing as much filter surface as possible in a prepared filter.

Typical types of constructions are:
- Rigid filter cells
- Pocket filters

Rigid filter cells
Here, the filter medium with an overall thickness of approximately 50 mm of a cardboard frame is supported with a perforated metal sheet or carton. Another form of design is a medium folded in pleats (⇒ larger surface). The medium is kept apart with the help of spacers made from cardboard or synthetic.
Pocket filter
Pocket filters are the most common construction type for fiber filters, where installments like v-shaped seams, individual stitching threads or stitched fleece strips etc prevent an inflation of the pockets. The filter is made up of 6 to 12 pockets which are housed in a joint frame.

Pocket filters have a particularly high dust-holding capacity and small installation dimensions.

- Surface ratio filter surface/reference surface: $\approx 20:1 \ldots 25:1$
- Velocity of approach: $\approx 2.5 \text{ m/s}$ (relates to reference surface), $\approx 1 \text{ m/s}$ (relates to filter surface)

Pocket filters are usually not cleanable but have a long service life.

Aerosol filters
Aerosol filters are solely used as the end stage in multistaged filters (e.g. prefilters are imperative). They are mainly used for special purposes in laboratories, operating rooms, clean rooms and in pharmaceutical companies.
Aerosol filters are often implemented in individual frames with the filter material arranged in pleats. The effective surface is 20...50 times larger than the approach surface. This produces an air velocity of $\approx 2.5 \text{ cm/s}$ at an approach velocity of $\approx 1.5 \text{ m/s}$ in the filter medium.

During the installment, it is important to pay attention to a seal-tight connection and most importantly to examine it.
In clean rooms, it is especially important to keep an eye on the pressure drop – because of the high volume flow and the continued operation – as it is a considerable contributor to energy consumption. Thus, newer developments in the filter classes H 13...H17 aim for a lower initial pressure difference (e.g. 90...150 Pa). Here for example, electrostatic and mechanic precipitations are combined which result to an even lower initial pressure difference (e.g. 55...90 Pa).

**Fig. 6-11  Aerosol filters (source: Filteron)**

**Metal filter**

Metal filters are used to separate oil and fat mists, coarse dust and color mist.

The filtering effects are dependent on how the air flow in the flow through of the filter layer is disassembled from a great number of partial flows, which in turn creates multiple changes in direction. The mechanism of separation is based on the barrier and inertial effect.

**Fig. 6-12  Metal filter (two possible construction types)**

The cleaning takes place by washing it out with detergent (e.g. with filters of cooker hoods) or with oil or solvents (depending on the type of air pollution).

**Activated carbon filter**

Filters with activated carbon are intended for the adsorption of harmful or unwanted gaseous and vaporous pollution of the air. That also includes smells from kitchens, toilets, assembly rooms but also gases and vapors from industrial processes.

The effect of active carbon filters are based on the physical and/or chemical adsorption, depending on the state of the harmful substance or the carbon.
The base material for activated carbon is black coal, coconut shells or wood. The base material is treated in a special process to produce an end product that is highly porous. The base material thus has an exceptionally large surface area where the contaminant molecules accumulate. Nevertheless, the outer surface can be small.

In contrast to the visible, macroscopic format and surface area, we refer to the surface area represented by pores as the "internal" or specific surface area of the activated carbon.

Reference points:
- Volume: 1 g activated carbon \( \cong \) ca. 2 cm\(^3\)
- Inner / specific surface: 900…1,200 m\(^2\)

To enable an activated carbon filter to also filter out specific contaminants, the adsorption surface area often has to be treated, i.e. impregnated, with a chemical agent. Optimum adsorption necessitates for the activated carbon, the chemical agent used, the impregnation and the substance to be adsorbed to be coordinated well. Activated carbon cannot adsorb gases such as N\(_2\), O\(_2\) and CO\(_2\), as these gases are always present, and the activated carbon itself already contains these molecules.

Activated carbon filters are available in various structural shapes, for example as activated carbon plates or regenerative activated carbon filter cartridges. The reactivation processes (e.g. high temperature treatment) varies considerably, depending on the adsorbed contaminant.

![Activated carbon filters (different structural shapes)](image)

Pre-filters are absolutely essential to ensure that the efficiency of the activated carbon is not impaired by contamination with dust. An activated carbon filter has a service life of 3…12 months, if installed and maintained correctly.

**Electric filter**

Electric filters with ionization part

Electric filters mostly operate according to the Penney system and consist of an ionized part with positive charged tungsten wire. Therein the arriving dust particles are charged by the ions via accumulation. The other part that makes up an electric filter is a dust precipitation part in the form of a plate capacitor.

The surface area can be sprinkled with dust binding agent, depending on the type of particles that need to be filtered. Cleaning is done by hosing with water at about 30…40 °C and can also be automated with the help of certain features.

Electronic filters offer a high degree of dust extraction also with the smallest parts of 0.1 \(\mu\text{m}\) and smaller (e.g. tobacco smoke, fog, pollen, bacterias). They provide a low air resistance but are also very expensive to purchase.
Electrostatic filter
In some cases, electric filters without an ionized part and that operate according to the electrostatic principle are used. In this case, fibrous materials can be used as filter media. These are either equipped with electric dipoles thanks to a special process or are arranged according to an external electrostatic field. Depending on the applied voltage or the structure of the filter medium, reduction efficiencies of 15 % up to 90 % are reached with or without electric field respectively.

Electric filters are increasingly provided in small installations in living areas, as they also remove pollen etc. Here, it is important to keep in mind that the energy consumption of the electric filter counteracts the goals of conserving energy by means of controlled residential ventilation systems (see 6.8).

6.4.5. Fans

Function
Transport of air through the air conditioning plants. They generate the required volume flow and the increase in pressure corresponding to the pressure loss in the plant.

![Radial fan](image)

**Fig. 6-14  Radial fan (source: Fachinstitut Gebäude-Klima e.V.)**

Design and operating principle
A distinction is made between radial fans (Fig. 6-15) und axial fans (Fig. 6-16).

In principle, radial fans are used in ventilation and air conditioning systems for relatively small amounts of air (up to about 50,000 m$^3$/h) at high supply pressures (up to 3,000 Pa).

Axial fans are used for relatively great amounts of air (> 50,000 m$^3$/h) at low supply pressures (up to 1,000 Pa).

Radial fans
The radial fan draws in the air by axial flow and delivers it by radial flow. The spiral casing is designed to guide the air. The impellers can be fitted with either forward curved, backward curved or straight blades, if necessary.

<table>
<thead>
<tr>
<th>Design</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backward curved blades</td>
<td>At high pressures up to 3,000 Pa and an efficiency of 80 ... 85 %</td>
</tr>
<tr>
<td>Forward curved blades</td>
<td>At low pressures up to about 1,300 Pa and an efficiency of 55 ... 75 %</td>
</tr>
<tr>
<td>Straight blades</td>
<td>For special applications</td>
</tr>
</tbody>
</table>
Axial fan
The axial fan moves the air flow parallel to its driving axle. The discharge swirl caused by the impeller is absorbed by a fixed guide wheel in the better and more powerful variations.

<table>
<thead>
<tr>
<th>Design</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall-mounted fan without impeller</td>
<td>For installations in walls or windows at low pressures (of about 300 Pa)</td>
</tr>
<tr>
<td>Wall-mounted fan with impeller</td>
<td>For installations in walls or windows at higher pressures (of about 1,000 Pa)</td>
</tr>
<tr>
<td>Counter-rotating (2 counter-rotating impellers)</td>
<td>For the highest pressures (&gt; 1,000 Pa) and special applications</td>
</tr>
</tbody>
</table>

The correct selection of the fan type is dependent on various aspects. Each type has certain advantages.

<table>
<thead>
<tr>
<th>Radial fan</th>
<th>Axial fan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low noise levels</td>
<td>Requires little space</td>
</tr>
<tr>
<td>Simple performance adjustments *</td>
<td>Inexpensive to purchase</td>
</tr>
<tr>
<td>Simple motor replacement *</td>
<td>Controlled by blade adjustment</td>
</tr>
</tbody>
</table>

*with motors with v-belt drive
Fan and plant characteristics

Principle of proportionality

For plant systems with square characteristics and unchangeable density, the Laws of Proportionality from fluid mechanics apply. (Square characteristics are applicable to almost all the components (see Fig. 6-17, Plant characteristics I and II)

Law of Proportionality 1:
The volume flow changes proportionally to the speed ratio.

\[
\frac{V_1}{V_2} = \frac{n_1}{n_2} \quad \text{(Equation 1)}
\]

Law of Proportionality 2:
The pressure increase changes with the square of the speed or volume flow ratio.

\[
\frac{p_1}{p_2} = \left(\frac{V_1}{V_2}\right)^2 \left(\frac{n_1}{n_2}\right)^2 \quad \text{(Equation 2)}
\]

Law of Proportionality 3:
The drive power changes proportionally to the 3rd potency of the speed or volume flow ratio. (This is only applicable if the fan efficiency doesn’t change)

\[
\frac{P_1}{P_2} = \left(\frac{V_1}{V_2}\right)^3 \left(\frac{n_1}{n_2}\right)^3 \quad \text{(Equation 3)}
\]

Statement of the equation

Equation 1 says e.g. that a duplication of the volume flow is achieved with the duplication of the rotation speed.

Example:

If the rotation speed of the fan is increased from 1,000 to 2,000 min⁻¹, then the forwarded volume flow of 4,000 m³/h changes as follows:

\[
\frac{V_1}{V_2} = \frac{n_1}{n_2} \Rightarrow V_2 = V_1 \cdot \frac{n_2}{n_1} \quad \text{and} \quad V_2 = 4000 \frac{m^3}{h} \cdot \frac{2000 \text{ min}^{-1}}{1000 \text{ min}^{-1}} = 8000 \frac{m^3}{h}
\]

Equation 2 shows for example that the duplication of the volume flow creates a fourfold resistance in the duct network that needs to be overcome and which needs to be raised by a fan.

Example:

The fan conveys the 4,000 m³/h with a pressure of 350 Pa. It is calculated as above, duplicating the rotation speed and the volume flow, resulting in the following pressure increase:

\[
\frac{p_1}{p_2} = \left(\frac{V_1}{V_2}\right)^2 \left(\frac{n_1}{n_2}\right)^2 \Rightarrow p_2 = p_1 \cdot \left(\frac{V_2}{V_1}\right)^2 \quad p_2 = 350 \text{ Pa} \cdot \left(\frac{8000 \frac{m^3}{h}}{4000 \frac{m^3}{h}}\right)^2 = 1400 \text{ Pa}
\]

Equation 3 shows e.g. that the duplication of the volume flow necessitates the eightfold of power or the other way around, the halved volume flow reduces the power consumption to 1/8 (see rotation speed control)!

Note: This is correct for theoretical, ideal conditions (loss-free). In practice (\text{ }^2 \cdot ^{2.5} )
Example:
If the fan is installed in a variable air volume system (VAV) plant and only needs to convey 4,000 m$^3$/h instead of 8,000 m$^3$/h, then the power consumption of current 3.0 kW (at the axle) as follows:

\[
\frac{P_1}{P_2} = \left(\frac{V_1}{V_2}\right)^3 \Rightarrow P_2 = P_1 \cdot \left(\frac{V_2}{V_1}\right)^3 = 3.0 \text{ kW} \cdot \left(\frac{4000 \text{ m}^3/\text{h}}{8000 \text{ m}^3/\text{h}}\right)^3 = 0.375 \text{ kW}
\]

![Fan and plant characteristic curve](image)

Fig. 6-17  Fan and plant characteristic curve

\(n_1,...n_4\) Fan characteristic curve at various speeds  
I, II  Plant characteristic curve 1 and 2  
1,...4 Operating points

1 Operating point normal  
1→ 2 Operating point shift e.g. with additional resistances in the grid  
3 as with 2, but with the desired air volume flow  
1→ 4 Operating point shift due to increase in speed

The fan characteristic curve normally looks a bit different than shown above and displays a rather confusing amount of lines, curves and scales whose meaning and information at the chosen operating point aren’t always immediately apparent (see Fig. 6-18).

Usually, one to three lines are measured depending on fan size (volume, pressure, required power and speed). All the other pressure/volume characteristic curves displayed are projected via law of proportionality.

This means: Not every displayed pressure/volume characteristic curve is a measured one.

To simplify the way in which the data is displayed, fan manufacturers use what is referred to as a "log-log" format. The result is that the plant characteristics are no longer shown as parabolas as in Fig. 6-17, but as straight lines via the function \(\Delta p_i = f(\dot{V})\) e.g. 4 in Fig. 6-18.
Fig. 6-18 Fan characteristics (with logarithmically scaled $\dot{V}$ and $\Delta p$ axes)

1. Volume flow rate in 1,000 m$^3$/h (or m$^3$/s, l/s, ...)
2. Total pressure increase $\Delta p$ in Pa
3. Pressure/volume characteristic fan curve
4. Efficiency and plant characteristic
5. Required power in kW at the fan shaft
6. A-weighted noise level (dbA)
7. Discharge velocity $c_2$ in m/s (at an interval of 2.5 x impeller diameter)
8. Dynamic pressure $pd_2$ in Pa (resulting from discharge velocity; $pd_2 = \rho \cdot (c_2)^2/2$)
9. Fan speed
10. Circumferential velocity of the impeller in m/s

A. Operating point, e.g. at 4,000 m$^3$/h and 800 Pa
6.4.6. Air heating coils

Function

Used to heat the supply air to the required temperature (e.g. the supply air temperature of a room heating system)

Mechanical design based on operating media

- Finned-pipe heat exchanger (Fig. 6-19) operated with:
  - warm water
  - hot water
  - Water or refrigerant vapor
- Electric air heating coils (Fig. 6-21)

Air heating coils are used as pre- or reheaters in air heating and air conditioning plants.

Heat exchangers normally show a non-linear response in terms of the mass flow passing through them and the associated output. Depending on how they are constructed and on the supply temperatures, this so-called heat transfer characteristic varies from a steep curve to a shallow curve, as expressed by the "a-value". The characteristic curve of the heat exchanger is shown in relation to the maximum volume flow rate $\dot{V}_{100}$ and the maximum output $\dot{Q}_{100}$.
Electric air heating coils

Electric air heating coils have a number of built-in spiral heating elements which become hot as the current flows through them. They emit the heat acquired in this way into the air. They are installed in areas where there is no hot water heating, where the connection point is too far away, or, for other reasons, a low-temperature hot water (LTHW) heating coil cannot be used. Owing to the risk of fire, electric air heating coils require special safety arrangements and devices (e.g. safety thermostat, fan run-on,...).

Fig. 6-21 Electric air heating coils (steel pipes with integrated heating coils; source Loysch)

6.4.7. Chilled water cooling coils

Chilled water cooling coils are finned-pipe heat exchangers operated with supply/return water temperatures of e.g. 6/12 °C or 8/14 °C. Air cooling coils normally require a larger heat-transfer surface area than air heating coils, because the average difference in temperature between the surface of the cooling coil and the air is smaller. The requirement for a greater surface area is fulfilled in design terms by several rows of pipes arranged one behind the other. If the air is to be dehumidified as well as cooled, then the cooling coil must be connected hydronically as shown below, i.e. in a throttling circuit. If the air only has to be cooled, then a mixing circuit or an injection circuit with globe valve is acceptable.

Fig. 6-22 Cold water cooling coil for installation in the ventilation unit (source: Wolf)
6.4.8. Direct expansion air cooling coils

A finned-pipe heat exchanger which acts as the evaporator in a refrigerant cycle is installed directly in the air flow as a cooling coil. As a rule, this solution is reserved for compact air cooling units which also have a built-in compressor and condenser.

Fig. 6-23 Direct expansion air cooling coils
Possible design types

Fig. 6-24 Direct expansion air cooling coils
Showing detail of the refrigerant distributor

6.4.9. Humidifiers

Principles

- Humidification through the evaporation of water
- Humidification through the introduction of steam

Evaporative humidifiers

Evaporative humidifiers include air washers, water atomizers, surface water evaporators and cold vapor generators.

Air washers

Water is pumped from a reservoir into the spray nozzles distributed in the air flow. The majority of the fine droplets evaporates and become water vapor, in the process of which the latent heat of vaporization is extracted from the air flow. Since the energy required for evaporation is taken solely from the air, the air cools down (adiabatic cooling). The non-evaporated water droplets are separated in a drip screen at the air washer outlet, and then routed back to the collecting tray.
Water atomizers

The water is converted by use of molecular atomizing nozzles into a fine spray mist. The water droplets (so called "aerosols") are so small that they are initially suspended in the air, and then evaporate completely. The latent heat of vaporization is removed from the air, which becomes slightly cooler (adiabatic cooling).

Surface water evaporator

Porous ceramic plates with a large surface area are located downstream of the water atomizer described above. Any aerosols which have not yet evaporated are trapped by these plates and then evaporate completely (see Fig. 6-27).

Cold water vapor humidifier

In plants required to satisfy stringent hygiene requirements, cold water vapor generators can be used for humidification. Compared with the methods of humidification described above, the characteristic features of a cold water vapor generator are significantly reduced consumptions of water and energy. The incoming air is first made to vibrate by means of infrared sound generator, for example, or alternatively, it may be passed through a vortex grid designed to create turbulence. The water is then injected into the air at high pressure at high pressure (20 - 150 bar) through nozzles. The vibration or turbulence ensures that the air in this process is well mixed. In this case too, latent heat of vaporization absorbs the humidity in the air. This causes a drop in the temperature of the treated air (along the line of enthalpy in the h,x diagram).
In cold water vapor humidifiers, only as much water as necessary is atomized. There is therefore no recirculation of the water, and no collecting tray. Any un-evaporated droplets are trapped in the drip screen at the end of the unit.

Cold water vapor generators make very good humidifiers (with humidification efficiency close to 100%). Their output is controlled by adjusting the water pressure in the atomizer nozzles.

### Steam humidifier

**Principle**

Water is fully evaporated first, and only then is it injected into the air (there is no adiabatic cooling of the air). Steam humidification is becoming increasingly common in comfort air conditioning plants, and is gradually replacing the use of evaporative humidifiers in plants where there is no requirement to cool the air at the same time. Steam is hygienic, clean and free of bacteria.

Steam humidifiers with self-generated steam

The evaporator (see Error! Reference source not found.) contains heating electrodes which degrade over time. Further, because the lime scale from the water remains in the evaporator, the entire evaporator has to be replaced at regular intervals. Modulating control of these steam humidifiers can be arranged, subject to the appropriate electronic interfaces.

![Steam humidifier, principle](image)

**Fig. 6-29  Steam humidifier, principle**

1. Evaporator (electrode boiler)
2. Electrodes
3. Steam ejector
4. Condensate pipe
5. Connection to water supply

Steam humidifiers with external steam supply

In large plants (industrial plants) with a correspondingly higher humidifier capacity, the steam is generated in a separate steam boiler. The steam, free of condensate, is injected into the air flow via a specially constructed steam manifold (Fig. 6-30). Any condensate which collects in the manifold must be fully drained and fed back into the steam boiler. A modulating control valve controls the exact quantity of steam released.
6.4.10. Dehumidification

There are three fundamentally different methods for removing humidity from the air:

- Cooling the air, so causing the water to condense
- Absorption of water in hygroscopic liquids
- Adsorption of the water vapor (steam) on solid surfaces

Cooling with condensation

This method of drying the air involves cooling the air with a cooling medium which is cold enough to condense the water in the air. This humidification process is therefore simultaneously an air cooling process.

It is noteworthy that the air does not necessarily have to be cooled to its dew point temperature. It is sufficient if the temperature of the cooling surface is below the dew point temperature of the air. The chiller does not even have to be very large. This is because even cooling the air very slightly causes condensation.

The same refrigerants normally used for cooling can be used for humidification, i.e. chilled water (produced in a chiller or refrigeration machine), well water, lake water, brine etc., and the various refrigerants used for direct cooling.

Air conditioning plants frequently use this principle to dehumidify the air while simultaneously reducing its temperature. The same method is also common in mobile units, which can be used irrespective of their location.

Absorption in liquids

Here the water is dissolved in hygroscopic liquids, thereby diluting the liquid. The amount of vapor absorbed increases with the concentration of water vapor in the air, with increasing pressure and with falling temperatures. Hygroscopic liquids are normally regenerated by heating.

The most commonly used hygroscopic liquids are salt solutions of lithium chloride, lithium bromide or calcium chloride in water.

Adsorption on surfaces

With this method of dehumidification, the water vapor collects on the surface area of a solid body, the adsorbent, which is made up of the smallest possible pores.

The usual material for the adsorption of water vapor is sodium silicate, better known as silica gel. It consists of 90% SiO₂ and has an internal surface area of around 1,000 m²/g.

In the adsorption process, the heat of adsorption contained in the adsorbent is released, causing the air to rise in temperature. It may therefore be necessary to cool the air after dehumidification by this method.
The adsorbent is regenerated by heating to approximately 150 °C ... 200 °C. Once the sorbent has cooled down again, it is ready for re-use.

For continuous operation of an adsorption plant, two silica-gel containers are required. One adsorbs the moisture in the air while the other is being regenerated and cooled.

The principle of adsorption for dehumidification of the air is put into practice in DEC (desiccative and evaporative cooling) plants (see 6.5.6). The rotating exchanger in these plants consists of a compound of ceramic material and silica gel. However, the temperatures required for regeneration are not as high, and this means that that the waste heat can be utilized.

6.4.11. Heat recovery

The system of heat recovery is discussed in detail in a following, separate chapter (see 6.5).

6.4.12. Air outlets

After the air has been processed according to the user demands in the central air processing unit, it is lead into different rooms via duct network. It is important that the air is lead into the room in such a way that the comfort of the room user is not affected. A great amount of different air outlets from various manufacturers are available to optimally lead the air into the room.
6.5. Heat recovery

6.5.1. Definition

Heat recovery is a collective term for the procedure of heat transfer to rehabilitation of thermal energy in a process with at least two mass fluxes, which possess various levels of temperature.

![Diagram of heat recovery](image)

Fig. 6-33 Heat recovery (and mixing of recirculated air) in an air conditioning plant

6.5.2. Aim

The aim of heat recovery is to minimize the primary energy demand which is required for controlling the temperature of outside air so to keep the supply air at the desired temperature. Thus, heat recovery can be seen from either an efficiency measure’s point of view or from a regenerative energy source point of view as the waste heat of the heat transfer process is regenerated useful. Heat recovery is therefore a regenerative process and an intelligent contribution to climate protection in all respects.

The demands on the heat recovery systems are established in the VDI ventilation regulations (VDI 3803, part 5).

6.5.3. Categorization of heat recovery systems

- Mixing of circulating air (no heat recovery mix. VDI 3803)
- Recuperative systems (plate heat exchanger)
- Regenerative systems (rotating heat recovery, CCS, …)
- Heat pumps

Mixing of circulating air

Mixing of circulating air is not the kind of heat recovery in the terms of VDI 3803 but rather avoiding unnecessarily losing energy due to exhaust air.

A pure mixing of circulating air theoretically makes it possible to use the entire exhaust heat. In praxis, the use of circulating air is limited if fresh air supply is required or hygienic concerns regarding the re-use of the consumed exhaust air exist (accessible ambient air quality).

The mixing of circulating air won’t be used as often in new systems yet it is still broadly in use in older systems.
Fig. 6-34  Mixing of circulating air

1  Outside air damper
2  Exhaust air damper
3  Recirculating air damper

If on hygienic grounds, the percentage of circulating air is not allowed to go over around 50 % is usually worthwhile in a combination of mixing of circulating air with a heat recovery unit.

Recuperative systems
In recuperative heat recovery, the heat is directly transferred through a solid partition from the exhaust air flow to the supply air flow. Material transmission is impossible. Depending on the type, it is referred to as a plate heat exchanger or tube heat exchanger.

The output control takes place in a bypass damper (normally installed in the outdoor air) which partially leads the outdoor air past the heat exchanger and simultaneously prevents the exhaust air from cooling off too much and thus from freezing over.

Regenerative systems
In the regenerative heat exchanger systems, the heat is transferred indirectly from the exhaust air to the supply air, i.e. from storage mass or an intermediate medium respectively. Mass transfer may be possible (dependent on heat recovery).
Combined circulation system (CCS)

A cooling grid in the extract air and a heating grid in the outdoor air are connected via supply and return flow. The pipe system is filled with water/ frost protection. A pump circulates this heat carrier medium. The cooling grid in the extract air absorbs heat and transfers it to the heat medium cycle. It transports the heat to the heat grid in the outdoor air.

A material exchange on the airside is not possible!

Thus, this solution is used in cases, where no mixture of air flows is allowed to take place or where the supply air plant and return air plant are located in two different locations in the building itself (e.g. in reconstruction situations, during plant renovations,…).

The control happens via three-port valve in the intermediate medium as shown in Fig. 6-36. The valve is placed as close as possible to the outdoor air heat exchanger and sized according to the regular standards. In plants with widely varying air streams, the maximum rotated intermediate medium of the pump needs to be adjusted according to the air mass flow rate, for example via speed control. This is why the water value ratio (heat flow of the air / heat flow of the intermediate medium) of 1 is met and the plant thus operates at an optimal total degree of change.

With a clever combination of a speed controlled pump and a 2-way valve (see Fig. 6-37) the CCS heat recovery can be operated flexibly in a large area and no unnecessary heat medium liquid is rotated. This leads to a significant reduction of the pump’s power consumption at part load operation. If the pump reaches a minimum speed, a straight way valve is employed and regulates the output at low-load operation.
**Rotary heat exchangers**

Rotating, cellular storage mass alternatingly flows through from outdoor air and waste air. The measurement of the heat exchange can be influenced by changing rotor speed. Due to the hygroscopic coating of the storage surface, humidity and enthalpy respectively can be transferred (sorption exchanger).

The constructions employed in the ventilation and air conditioning technology rotates the storage mass continuously with about 1…10 rotations per minute [min⁻¹] between the outdoor air and exhaust air canal. The degree of change depends on the rotor speed and the inflow air velocity.

![Heat recovery, rotary heat exchanger](source: Wolf)

**Switching heat exchanger**

The switching heat exchanger unit contains two or more static heat accumulator bundles made from aluminum sheets (static storage). Outdoor and exhaust air alternately flow through these aluminum sheets. The control takes place via changeover dampers which operate electromotive and dynamically in short switching times. The hot exhaust air charges the storage; the passing cold outdoor air discharges it.

![Heat recovery switch heat exchanger](source: Wolf)

The switch heat exchanger requires no anti-freezing protection. The power control is controlled load-dependently with the switching of the flaps.
Heat pipes

The heat pipes build a refrigerant cycle without supply of auxiliary energy. From the outside, the heat pipe exchangers look like the standard heating or cooling grids. Though, the heat pipes are installed where the tube coils would be. They operate independent from each other. The heat pipes are made of air-tight (evacuated) lamella pipes. On the inside, these lamella pipes contain a refrigerant. The hot exhaust air flows through the lower part of the heat pipe and heat the refrigerant. It evaporates, rises to the upper part and transfers the evaporation heat to the cold outside air.

Heat pipes are used in large air conditioning plants and in process engineering, among others.

Heat pipes don't require any maintenance or anti-freezing protection. The output control is relatively difficult and can for example be realized via bypass or by changing the tilt angle with the help of an actuator.

Anti-freezing protection in heat recovery

If the interior air, which is lead through the heat recovery, shows a high percentage of humidity, it can condense by it cooling down in the heat recovery. If it is cooled down extensively (low outdoor air temperatures during winter), then the condensate can even freeze, which reduces or even blocks the exhaust air flow in the heat recovery unit as a result. Thus, the exhaust air fan is greatly strained while super pressure is created in the ventilation system. This must be prevented with the appropriate measures. More information concerning this can be found in the documentation “Control of ventilation and air conditioning plants”.

The recuperative heat recovery and the CCS heat recovery are in the greatest danger of freezing. It will only become critical for the rotating heat exchangers at very low outdoor temperatures. As mentioned above, there are heat recovery systems which don't require anti-freezing protection.
**Heat pump**

A heat pump is a machine that can provide usable heat, which is largely taken from a medium (air, water). The medium serves as a heat source. Often, the extracted heat is environmental heat (anergy) free of charge or exhaust heat that can't be used anything else. They are "pumped" to a higher temperature level, as is required so that it can be used.

In ventilation technology, heat recovery is also possible with heat pumps. The heat pump withdraws heat from the exhaust air and leads it to the inflowing, cold outside air. The process is also reversible (summer/cooling).

Heat pumps also operate at low useful heat (low-temperature) where conventional heat recovery systems are impossible to use.

In this application, there are disadvantages with the heat pump:

- Simple heat pumps transport the heat in only one direction. If the direction of the heat transfer should be changed, e.g. the cooling mode of the plant, then the heat pump needs to be equipped with an additional reverse circuit.
- The plant requires a relatively high investment and maintenance costs (mostly electricity as operating power).

![Heat pump, principles](source: Wolf / robatherm)

The heat pumps are used as compression or absorption heat pumps in ventilation technology. They are thus rather suitable as heat recovery systems in industrial plants where e.g. relatively constant quantities of process heat have to be lead away via ventilation system.

Often, the heat pumps are used because of their small space requirements in compact air conditioning plants.
6.5.4. Efficiency of heat recovery systems

Degree in change of temperature $\Phi_t$ (heat recovery efficiency)

The degree in change of temperature $\Phi_t$ indicates the relation of the change in temperature of the outdoor air of a heat recovery at the highest change in temperature possible (difference between outdoor air and extract air temperature):

$$\Phi_t = \frac{t_{22} - t_{21}}{t_{11} - t_{21}} = \frac{\text{actual heat transfer}}{\text{possible heat transfer}}$$

The degree in change of temperature is defined under “dry conditions”, that is without condensation.

---

**Categories of heat recovery as per DIN EN 13053**

<table>
<thead>
<tr>
<th>Category</th>
<th>Energy efficiency $\eta_e$ [%]</th>
<th>Definition of the energy efficiency values</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>$\eta_e \geq 71$</td>
<td>$\eta_l$ = 0.75, $\Delta p_{WRG}$ = 2 x 280 Pa, $\varepsilon$ = 19.5, $\eta_e$ = 0.71</td>
</tr>
<tr>
<td>H2</td>
<td>$71 &gt; \eta_e \geq 64$</td>
<td>$\eta_l$ = 0.67, $\Delta p_{WRG}$ = 2 x 230 Pa, $\varepsilon$ = 21.2, $\eta_e$ = 0.64</td>
</tr>
<tr>
<td>H3</td>
<td>$64 &gt; \eta_e \geq 55$</td>
<td>$\eta_l$ = 0.57, $\Delta p_{WRG}$ = 2 x 170 Pa, $\varepsilon$ = 24.2, $\eta_e$ = 0.55</td>
</tr>
<tr>
<td>H4</td>
<td>$55 &gt; \eta_e \geq 45$</td>
<td>$\eta_l$ = 0.47, $\Delta p_{WRG}$ = 2 x 125 Pa, $\varepsilon$ = 27.3, $\eta_e$ = 0.45</td>
</tr>
<tr>
<td>H5</td>
<td>$45 &gt; \eta_e \geq 36$</td>
<td>$\eta_l$ = 0.37, $\Delta p_{WRG}$ = 2 x 100 Pa, $\varepsilon$ = 26.9, $\eta_e$ = 0.36</td>
</tr>
<tr>
<td>H6</td>
<td>$\eta_e &lt; 36$</td>
<td></td>
</tr>
</tbody>
</table>

Calculation of the energy efficiency values ($\eta_e$) with:

Degree of temperature transfer HR:

$$\eta_l = \left(\frac{t_{\text{Supply air}} - t_{\text{Außenluft}}}{t_{\text{Extract air}} - t_{\text{Outside air}}}\right) [%]$$

Pressure loss HR:

$$\Delta p_{HR} = \Delta p_{HR, \text{Supply air}} + \Delta p_{HR, \text{Extract air}} [\text{Pa}]$$

Electrical auxiliary energy HR:

$$P_{el, HR} = q_v \times \Delta p_{HR} \times 1/0.6 + P_{el, Aux} [\text{W}]$$

Performance figure HR:

$$\varepsilon = Q_{HR} / P_{el, HR} [-]$$

Energy efficiency HR:

$$\eta_e = \eta_l \times (1 - 1/\varepsilon) [%]$$
6.5.5. Features of heat recovery systems

An evaluation of transfer behavior concerning pollutants and odors, on the basis of VDI 2071, regarding ventilation systems:

<table>
<thead>
<tr>
<th>Heat recovery system</th>
<th>With heat exchangers</th>
<th>Heat recovery efficiency</th>
<th>Humidity recovery efficiency</th>
<th>Transfer behavior in case of</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>odors</td>
</tr>
<tr>
<td>Recuperative systems</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plate heat exchangers</td>
<td>0.4 - 0.8 *</td>
<td>0.0</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>Plate heat exchangers (humidity-permeable films)</td>
<td>0.4 - 0.8 *</td>
<td>0 - 0.8</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>Pipe bundle heat exchanger</td>
<td>0.3 - 0.5 *</td>
<td>0.0</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>Regenerative systems</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circuit combined systems (CCS)</td>
<td>Compact heat exchanger</td>
<td>0.3 - 0.5</td>
<td>0.0</td>
<td>+</td>
</tr>
<tr>
<td>Counterflow layer heat exchanger</td>
<td>0.7 - 0.8</td>
<td>0.0</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Heat pipes</td>
<td>Gravity heat pipe (thermosiphon)</td>
<td>0.2 - 0.4 *</td>
<td>0.0</td>
<td>o</td>
</tr>
<tr>
<td>Capillary heat pipe</td>
<td>0.5 - 0.8 *</td>
<td>0.0</td>
<td>o</td>
<td>o</td>
</tr>
<tr>
<td>Regenerators</td>
<td>Rotor with sorption</td>
<td>0.7 - 0.8 *</td>
<td>0.6 - 0.7</td>
<td>o</td>
</tr>
<tr>
<td>Rotor without sorption</td>
<td>0.7 - 0.8 *</td>
<td>0.1 - 0.2</td>
<td>o</td>
<td>-</td>
</tr>
<tr>
<td>Others</td>
<td>Capillary blower</td>
<td>0.2 - 0.4 *</td>
<td>0.2 - 0.4</td>
<td>--</td>
</tr>
<tr>
<td>Switching storage</td>
<td>0.6 - 0.9 *</td>
<td>0.5 - 0.7</td>
<td>--</td>
<td>--</td>
</tr>
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<td>Heat pumps</td>
<td>Compressor heat pumps</td>
<td>./</td>
<td>0.0</td>
<td>+</td>
</tr>
<tr>
<td>Adsorption heat pumps</td>
<td>./</td>
<td>0.0</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

(-) unsuitable  (+) Leakage and / co-rotation included
(-) less potential  (./) missing reference scale
(o) only suitable with help or special constructions
(*) suitable

Fig. 6-44 Features heat recovery (source: Wikipedia)
## Features of heat recovery systems

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Plate heat exchanger</th>
<th>Heat pipe</th>
<th>Rotation heat exchanger</th>
<th>Switching storage</th>
<th>Combined circulation system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Merged outdoor air and exhaust air duct</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Volumetric air flow</td>
<td>Small to medium</td>
<td>Small to medium</td>
<td>Small to medium</td>
<td>Small to medium</td>
<td>Small to medium</td>
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<tr>
<td>Contamination of draft possible</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>(at pressure drop from exhaust air into outdoor air)</td>
<td>no</td>
<td>no</td>
<td>yes a)</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Contamination of draft possible</td>
<td>no</td>
<td>no</td>
<td>yes a)</td>
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<tr>
<td>(at pressure drop from outdoor air into exhaust air)</td>
<td>no</td>
<td>no</td>
<td>yes a)</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Moisture transfer at condensation</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
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<td>Moisture transfer at sorption</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
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<tr>
<td>Indirect evaporative cooling</td>
<td>ja</td>
<td>nein b)</td>
<td>ja c)</td>
<td>nein</td>
<td>ja</td>
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<tr>
<td>Multifunctional use possible</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes d)</td>
</tr>
<tr>
<td>Auxiliary energy</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
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<tr>
<td>Leakage</td>
<td>small</td>
<td>small</td>
<td>significant</td>
<td>significant</td>
<td>no</td>
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<tr>
<td>Leakage in case of malfunction possible</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
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<tr>
<td>Frost hazard</td>
<td>high</td>
<td>medium</td>
<td>small</td>
<td>small</td>
<td>medium</td>
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<td>Cold recovery</td>
<td>yes</td>
<td>no b)</td>
<td>yes</td>
<td>yes</td>
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<tr>
<td>Maintenance costs</td>
<td>small</td>
<td>small</td>
<td>medium</td>
<td>medium</td>
<td>medium</td>
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<tr>
<td>Transmission of fire or smoke possible</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Limitation of max. pressure difference o fair flows necessary</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Constant pressure ratios possible</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
</table>

a) can be minimized or prevented by using a rinsing chamber
b) except with capillary heat pipe or tilt control
c) if moisture transfer can be excluded (no sorption pipe permitted)
d) reasonable as of a degree of change in temperature from 70 % onwards

Fig. 6-45 Features of heat recovery (source: VDI 3803, part 5)
6.5.6. DEC systems

DEC stands for “Desiccative and Evaporative Cooling”. The basic thought underlying DEC technology is to replace the conventional generation of cooling energy in air conditioning plants (with electrically operated compressors) with evaporative cooling as well as heat and humidity exchangers. Here, the familiar process of adiabatic cooling is used in a special combination with adsorptive dehumidification (see 6.4.10). Usually, solid sorbents with a proven record are used (e.g. silica gel). The motive energy for this process (see 5 in Fig. 6-46) is heat, at not too high a temperature, which is often available in the form of waste heat – especially in summer. From the diagram below, it is evident that this process takes place at a relatively high temperature compared with the air temperature (regenerative air heaters up to e.g. 70 °C).

Principle of operation (in summer)

After the normal filtering process, the outside air (e.g. at 32 °C and 35% RH) is dehumidified in an adsorption heat exchangers (1). This dehumidification is a continuous process, and virtually adiabatic. The heat of adsorption released in this process is emitted into the air flow, thereby heating up the outside air.

The dry, warm air is then pre-cooled in a regenerative heat exchanger (2). In winter, this rotary heat exchanger used to preheat the outside air via extract air. The thus pre-cooled air is then passed through an evaporative humidifier (3) which takes it to the required supply air temperature and humidity.

In a second evaporative humidifier (4), the extract air temperature is reduced to enhance the pre-cooling of the supply air in the heat recovery (2). The extract air is heated in this process. The air coil heater (5) is then used for reheating, in order to regenerate the adsorption heat exchanger (1). This causes the extract air to cool down, and the humidity to increase. This process is also referred to as “adiabatic desorption”.

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Fig. 6-46 Principle of operation of a DEC system – in summer (source: Klingenburg)

1. Sorption exchanger (drying of the outside air)
2. Rotary heat exchanger
3. Supply air humidifier (adiabatic cooling)
4. Extract air humidifier (adiabatic cooling, e.g. cold vapor generator)
5. Regenerative heating coil (heats the air to e.g. 70 °C)

I. State transition of outside air → supply air (ODA → SUP)
II. State transition of extract air → exhaust air (ETA → EHA)
6.6. **Air conditioning with central energy supply**

Ventilation systems which can keep a predetermined condition of air as per temperature and humidity throughout the year are referred to as an air conditioning plant. It is also equipped with all necessary components that allow the air to be heated or cooled, humidified or dehumidified, as required.

The requirement of application of an air conditioning plant has to respectively be checked thoroughly. Subsequently, some specifications which make air conditioning necessary:

- Heat, humidity
- Architectural standards such as great window facades, open-plan office, insufficient shading, ...
- Strict requirements to temperature and humidity
- Rooms on the inside, meeting rooms
- High thermal loads
- Electronic services, engine rooms

Air conditioning plants with a central heat and / or cooling generation are generally differentiated according to the transportation of the required heat and cooling energy of a room:

- Solely via supply air
- Solely via hot water and cold water distribution nets
- Via supply air as well as hot water and cold water distribution nets

From these differentiations result the following system variants:

- All-air systems
- Air/water systems

Here, it should be observed that the energy transfer of the same heat and cooling output in an all-air system requires significantly more energy than the transfer via water.

![Diagram of air conditioning plants](image.png)
6.6.1. **All-air systems**

The required heating and cooling energy is delivered to the rooms solely via the supply air. The heating or cooling energy prepared in the energy control center transfers it’s heating and cooling energy respectively to the supply air in the primary air handling plant.

**Fig. 6-48** Types of air conditioning plants

**Fig. 6-49** All-air system

1. Outside air
2. Exhaust air
3. Supply air
4. Extract air
5. Room
6. Recirculating air
7. Primary air handling
8. Air ducts (supply and extract air)
9. Boiler
10. Refrigerating machine

**Single-duct system without zone secondary treatment unit**

In this system (Fig. 6-50), the entire volume of supply air is prepared in the primary plant and then delivered to the rooms via duct system. The output is adjusted according to the basis of the extract air conditions; this takes place in the primary plant only.

Plants with primary air handling are only suitable for air conditioning in open-plan offices as well as in groups of rooms with equally varying loads. Varying loads which constantly differ from one individual room or zone to another can only be accommodated by modifying the air volume at start-up.
**Single-duct system with zone secondary treatment unit**

In this type of system (Fig. 6-51), the supply air, prepared in the primary plant, is delivered via single-duct system to the rooms or zones which require air conditioning. The air duct system can be sized for low or high velocity delivery. In the latter case, expansion boxes are fitted in the rooms or zones before the air outlet.

The supply air, pre-treated in the primary plant, is post-treated in accordance with the required indoor air conditions in each individual room or zone. This secondary air handling, or "secondary treatment", may comprise reheating, recooling, re-dehumidification or re-humidification. In practice, however, secondary treatment tends to be limited to reheating.

In single-duct systems with centralized secondary treatment for the zones, the secondary treatment takes place immediately downstream of the primary plant. In this case, the low-temperature hot water, chilled water or steam pipes are therefore only installed in the plant room. The air ducts leading to the zones need to be heat-insulated, so that the energy transferred to the air in the secondary treatment process is not wasted in the distribution process.
Single-duct system with local secondary treatment

In single-duct systems with terminal secondary treatment (Fig. 6-52), the secondary treatment takes place close to the zones. This means that the energy source line needs to be insulated with hot water, cold water or steam in the entire building.

The secondary treatment unit is a normal finned tube heat exchanger and air humidifier as covered in chapter 6.4 “Aerotechnical plant elements”. The type of humidifier is significantly dependent on the installation site. If it is installed in the zone line in the utility room then all types can be used as all necessary supply and return line can be installed without great difficulty. Mostly, only steam humidifiers are come into question when locally installing in front of the zone.

This plant is often used in buildings with a limited zone number but relatively great zone surface area and thus a great supply air volume flow (> 1,500 m³/h).

The system is not suitable for a subtler zone division because of the space required for ducts. For the same reason, the zones should not be located too far away from each other or the primary plant itself. So to avoid a waste of energy, the essential supply air temperatures of the individual zones should not diverge too much from each other.
Multi-zone system with multi-zone primary plant

Multi-zone systems are ideal for buildings with a small number of zones but which require a relatively large volume of air (e.g. shopping centers or conference halls in hotels) and have different heating and cooling loads in each zone (Fig. 6-53). In the primary plant, the outside air and recirculated air are mixed, and then the entire supply amount filtered and preheated (Fig. 6-54). A partial flow is blown through the reheater while the other is

When it leaves the supply air fan, the supply air flow is split into two separate air streams. One of these passes through the reheater and the other across the cooling coil. The hot and cold air streams are then mixed via the zone dampers to provide the individual supply air temperature required for each zone. The zone dampers are arranged vertically, with a hot and a cold air damper on the same damper shaft. The cold air damper is set at an angle of 90° in relation to the hot air damper, so that whenever the cold air damper is closed, the hot air damper is fully open. The supply air is distributed to the individual zones by provision of the appropriate number of zone dampers.

The reheater is always located at the top and the cooler at the bottom, to ensure that possibly leaked condensate does not come into contact with the reheater, where it can re-evaporate.

Multi-zone systems are designed as low velocity systems. In terms of volume, this means that the ducts need to be relatively large, and therefore should not be routed over long distances. In addition, concerning consumption of heating and cooling energy (mixing losses), it is preferable if the supply air temperatures required in individual zones do not differ from each other too much (< 5°K).
Dual duct systems

This type of system can still be found in existing plants but is not constructed anymore because of observation on energy efficiency.

The term "dual duct" refers to two supply air ducts, one hot and one cold, which run and are lead parallel to each other into each room. As with the single duct systems, the extract duct is not taken into account here either.

The air duct system is mostly designed as a high speed system so to keep the space demand as little as possible. The catharsis of the air flow from high to low speed and the mixture of hot and cold air take place in the especially constructed mixing box. These are installed in the room. The mixing ratio is controlled by means of the room temperature control unit.

In the beginnings of air conditioning technology, when energy consumption was not seen as important yet, the hot and cold air ducts were operated at the same temperatures all year round. As a result, especially with low loads, energy consumption was unnecessarily high, because heating energy was used to compensate for cooling energy. Thus, a mixing air temperature of 20 °C, for example, was reached in the mixing chamber in the primary air conditioning plant. Half was then cooled to 10 °C while the other half was heated to 30 °C. At the end of this process, both air streams were mixed (yet again!) in the mixing boxes to a temperature of approximately 20 °C.

Once energy consumption became an important topic, planners stopped using dual duct technology until control technology eventually overcame the problem of unnecessary energy consumption in this otherwise convenient solution. Today, the supply air temperature setpoints do not remain constant. Instead, the hot-air temperature is always defined by the highest and the cold-air temperature by the lowest supply temperature setpoint transmitted by all the connected room temperature control units. Modern digital technology allows us to read the current values via a building bus and to select the maximum and minimum values at any given time. This helps reduce mixing losses. Rooms with the maximum cooling load will receive cold air only, while those with the maximum heating load will receive hot air only, and rooms with a moderate heating or cooling load will receive a mixture of hot and cold air.

The air for the cold air duct in the primary plant is taken to the right temperature and dehumidified. The air needed for the hot air duct is heated and possibly moisturized. The design according to Fig. with only partial, uncontrolled dehumidification by withdrawing water from the cold air flow thusly conforms to the standard solution for normal comfort demands.

Fig. 6-55 Dual duct system with partial dehumidification of the supply air

1 Outside air 2 Exhaust air 3 Supply air 4 Extract air 5 Dampers 6 Filters 7 Preheater 8 Humidifier 9 Supply air fan 10 Reheater 11 Cooler 12 Hot air duct 13 Cold air duct 14 Mixing box 15 Extract air fan

The mixing boxes are constructed for suspended ceiling or sub-window instillation. Normally, the air outlets function as outlet grille or ceiling diffuser.
Variable air volume systems (VAV)

The VAV system is basically a cooling system, and therefore, for heating purposes it must be combined with a suitable heating system (radiator heating or underfloor heating). The entire cooling output is provided by the supply air. The supply air temperature remains constant, and the room temperature is controlled by varying the volume flow rate of the supply air. There is no need to divide the building into zones, because the supply air volume flow rate can be individually matched in each room to the sensible cooling load. In a building with rooms exposed to all four directions of the compass, solar radiation represents one of the main cooling loads. However, because the sun moves round the building from east to west, the maximum cooling load is not the same in all rooms simultaneously.

The cooling output is proportional to the supply air volume flow rate. This means that the maximum volume flow rate required overall is significantly less than the sum of the maximum volume flow rates for each individual room. By use of suitable air diffusers, the difference in temperature between the ambient air and the supply air can also be increased significantly compared with conventional systems, making it possible to reduce the supply air volume flow rate yet further.

Today, the VAV systems in ventilation systems are often operated with air quality control (especially in commercial buildings), partially combined with the room temperature control.

In the VAV system illustrated in Fig. 6-56, the supply air prepared in the primary plant is passed via single duct system to the rooms to be conditioned.

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Fig. 6-56 Variable Air Volume system (VAV)

1. Outside air
2. Exhaust air
3. Supply air
4. Extract air
5. Dampers
6. Single zone primary plant
7. VAV boxes (supply and extract air)
8. Base load heating
9. Room

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Fig. 6-57 VAV box with measuring cross and fitted with a compact controller
(combination of volume controller and damper actuator; source: Trox Hesco, Siemens)
6.6.2. Air/water systems

Air routing in a room

Displacement ventilation

Large volumes of air are moved about in the room in the types of plants discussed thus far, which leads to high air velocity levels in the spaces occupied by people. Displacement ventilation can largely satisfy the ever more stringent demands placed on ventilation plants in relation to draught freedom and the removal of heat and contaminants.

With displacement ventilation, the treated air is introduced at – compared to the room temperature – a slightly insufficient temperature in the floor area and with a laminar or turbulence-free flow (Fig. 6-59).

The supply air temperature in office buildings should be lower than the room temperature by no more than 1…3 K (or up to 8 K in factories). At the same time, however, (to avoid cold drafts at footvel) it should not fall below 21 °C in offices or 17 °C in industrial premises, respectively. The discharge velocity is approximately 0.2 m/s in offices and up to 0.6 m/s in other applications. This allows the formation of a "cold air pool" in the occupied space. The thermal buoyancy created by people and equipment in the room causes the air to rise towards the ceiling, where it is extracted. Due to the fact that the cold air only rises towards the ceiling in the vicinity of heat sources, the heat and any contaminant load is removed directly where it arises, without being circulated throughout the room. This makes it possible to maintain good air quality with relatively small volumes of air (greater ventilation efficiency). The normal ventilation rate here is in the range 1…4 h⁻¹.

The ventilation principle described above only works with supply air at a relatively low temperature. Displacement ventilation plants are not suitable for room heating, because the hot air at the outlet would rise immediately. That is why there is a need for static heating using radiators or convection heaters under the window. This type of heating can also be used for base load heating when the air conditioning system is switched off.

A certain distance from the outlets needs to be kept so to ensure the thermal comfort in the occupied zones (see 3 in Fig. 6-59).

The dissipateable cool loads are small with insufficient temperature of 1 … 3 K of the supply temperature compared to the room temperature. Therefore, the displacement ventilation has to be combined with additional cooling surfaces in the room, e.g. chilled ceilings.

Range of application

Displacement ventilation is especially suitable for:

- Rooms, where the loads don’t differ greatly.
- Rooms, where the air quality plays a significant role (industrial warehouses, sports centers, hotels, theater, schools, restaurants).

Displacement ventilation meets high comfort requirements (especially in connection with chilled ceilings).
Chilled ceilings

Air is an unsuitable coolant. Consequently, air can’t lead enough cooling energy into the room because the air temperatures to insufflate can’t be chosen arbitrarily. That is the reason why an air conditioning system is very often combined with a static cooling element. An air conditioning system mainly has the role to renew the used air in the room. The static cooling element which is mounted on or installed in the ceiling (hence the term chilled ceiling) cools the room down to the desired temperature by using water as a coolant.

Sensible heat

The mechanisms which lead away sensible heat are:

- Thermal radiation (from all warmer surfaces in visual contact with the ceiling)
- Thermal convection (air which is cooled down at the ceiling and then drops).

In closed ceilings, the distribution is approximately 60 % radiation and 40 % convection. That is why these ceilings are referred to as radiant chilled ceiling. There are also other systems, where the convective share prevails which are described as convection chilled ceilings or convection chilled elements.

Today, customary radiant chilled ceilings offer a cooling capacity up to 125 W/m². Convection chilled elements offer even up to 160 W/m².

Dew point shortfall

The output limit in chilled ceilings is given by the chilled water flow temperature (usually about 15 °C ... 16 °C). The chilled water lines as well as at every position in the chilled ceiling itself are not allowed to fall below the dew point of the air in the room. The formation of condensate is then avoided for certain.

There are two ways of avoiding danger of a dew point shortfall:

With the dew point sensor at the cold water supply line

- the cold water pipe is blocked by means of a motor valve.
- the cold water flow temperature is elevated by means of control valve.

In buildings with chilled ceilings, it often is not possible to open the windows because otherwise the difficulty of dew point shortfall could arise increasingly.
**Fan coil units (fan or forced air convectors)**

The classic and most applied air/water system in the field of comfort air conditioning is the “fan coil system”. The term “coil” refers to the finned coil heat exchangers.

This combination of fan and heat exchanger can be found on the market as e.g. a compact chest-type unit which in addition contains a recirculation filter as well as control devices. These fan convector devices or so-called fan coil units (Error! Reference source not found.) are mounted on any desired wall of the room and to the cold and hot water net as well as the electric power grid. The installed fan aspirates the air in the room and blows it over the heat exchanger (where it is heated) and exits via supply air grids (4 in Error! Reference source not found.).

If the unit is fitted to an outside wall, a small proportion of outside air can be drawn in through a vent with a manually adjustable damper and mixed into the recirculated air.

---

**Fig. 6-60**  Chilled ceiling elements

**Fig. 6-61**  Fan coil unit, components

- 1 Control elements
- 2 Finned pipe heat exchanger
- 3 Fan
- 4 Adjustable supply air grid

**Fig. 6-61**  Fan coil unit with outside air component, system

- 5 Fan coil unit
- 6 Outside air unit with damper
- 7 Hot or cold water circuit
Fan coil systems with water/water heat pumps
A good way of operating a fan coil system is by using a water/water heat pump. Here, the condenser generates the heat for the heating circuit, and the evaporator generates the cooling for the cooling circuit. This configuration also provides optimum heat recovery between the heating and cooling circuit. Further, the hot water storage tank required for operating the heat pump can be combined with a solar collector circuit, because the hot water flow temperature for the heating circuit can be relatively low.

Fan coil units with direct evaporator air cooling coils
Fan coil units, which are fitted with direct evaporator air cooling coils make up the ventilation part of a split system (see 6.7.4). Additionally, hot water air heating coils or, rarely, electrical air heaters are installed for the heating operation.

Fan coil units are ideal air heating and cooling systems in hotel rooms.
In heating mode, a central heating which is regulated by the outside temperature (underfloor heating) supplies the base load. This means that the room temperature at economy mode is held at about 15 °C. The fan coil system in changeover in comfort mode reaches the desired comfort temperature within a few minutes. In all other rooms, the fan coil systems are not in use.

Fan coil units with primary air and induction systems
If the air conditioned rooms in a building require a constant proportion of outside air of at least one air change per hour while the building is in use. That may not be possible to achieve by opening windows at regular intervals. In such cases, the air is heated centrally and humidified, or depending on outside air conditions cooled centrally and dehumidified if necessary. It is then distributed to the individual rooms in the form of "primary air" via a high velocity or low velocity duct system. Fan coil units or induction units are located in each individual room to heat or cool the ambient air.

Fan coil units with primary air
The primary air is distributed in the building via a high velocity or low velocity duct system, and it can be discharged directly into the room, either through fan coil units (Error! Reference source not found.) or separate air diffusers (Fig. 6-62).

Fig. 6-62 Fan coil unit with primary air supplied via fan coil unit

1 Outside air
2 Exhaust air
3 Supply air
4 Recirculated air
5 Fan coil unit
6 Room
7 Primary air handling in the central plant
8 Boiler
9 Refrigerator
10 Alternative route for primary air supply
The air flow in a high velocity duct system has to be expanded to reduce it to a low velocity air flow before it is discharged into the room or fan coil unit. In principle, the heating or cooling load in the room or zone is handled by the water system. However, any necessary humidification or dehumidification can be carried out at the primary air handling stage. The primary air is normally discharged into the room at a constant temperature, which generally corresponds to the heating setpoint of the room temperature, so to avoid interfering with the room temperature control unit.

Induction systems
Nowadays, the induction system is a rather uncommonly used air/water system. It is suitable for the same area of application as a fan coil system with primary air. Like fan coil units, the induction units located in the rooms accommodate the necessary finned pipe heat exchangers to heat or cool the indoor or secondary air. Induction units do not require any fans. The centrally treated outside air is distributed through the building in the form of primary air via a high-velocity duct system and delivered to the individual induction units (Fig. 6-63).
Instead of a fan, the induction units contain a soundproofed primary air chamber with fitted plastic nozzles. The primary air is blown out of these nozzles at high velocity and into a mixing chamber. That generates negative pressure. This negative pressure sucked in (induced) and while doing so, is lead through the finned pipe heat exchanger where it is heated or cooled according as required (Fig. 6-64).

Depending on the type of construction, the induction ratio of primary air/secondary air lies between 1.2 and 1.4.

![Fig. 6-65 Induction unit](image)

1. Primary air
2. Secondary air (ambient air)
3. Supply air
4. Primary air port
5. Induction nozzles
6. Heat exchanger

The heat exchangers are supplied with hot or cold water as needed. The induced secondary air in the heat exchanger takes over the required secondary heat or cooling output and subsequently mixes with the primary air. The mixture of secondary and primary air is finally blown into the room.

The air distribution duct can only be sized for about 1/4 up to 1/5 of the air volume flow of an all-air system, because the primary air volume flow only corresponds to the required outdoor air proportion. Respectively, this reduces the space required for the duct system. In the induction system, the extract air is normally not directly sucked from the air-conditioned rooms. The entire extract air corresponding to the amount of primary air is sucked from the corridors, storage rooms, toilets, etc. and flows into the atmosphere in the form of exhaust air. Hence, a slight overpressure is generated in the air-conditioned rooms whereby a mixture of air from different rooms is prevented.

As with the fan coil plants with primary air, the heating or cooling load in the room or the corresponding room zone is usually taken over by the water system. However, the primary air can take on the required dehumidification or humidification, respectively.

The primary air is usually injected at a constant temperature which normally corresponds to the heating setpoint of the room temperature, so not to interrupt the room temperature control unit.
Als Spezial-Ausführung einer Induktionsanlage kann das Kühldecken-Induktionssystem bezeichnet werden.

A special design of an induction plant is the chilled ceiling induction system.

![Fig. 6-66 Chilled induction beam, cross section (source: Trox)](image)

ODA conditioned outdoor air
SEC secondary air (ambient air)
SUP supply air

Induction units, designed as chilled beams (Fig. 6-66), supply the primary air and cool the ambient air, while the room is heated with standard radiators or convector heating. The result is optimal, draft-free ventilation, because the system works on the basis of natural gravitational circulation of ambient air. The air which is heated in the room – and therefore lighter – rises to the ceiling, where it is cooled and mixed with primary air. It then sinks again, because of its now increased density.

**Hydronic connection of fan coil and induction systems**

The required heating and cooling energy is delivered to the rooms solely via the hydronic circuits. The hot or cold water prepared in the primary plant transfers its heating or cooling energy via fan coil unit (fan convector) or induction unit to the room air. These systems are therefore especially suitable for rooms, where there is no need for forced ventilation with outside air (e.g. hotel rooms with window ventilation).

**Two-pipe system**

In respect to the hydronic circuits, a distinction is made between two-pipe, three-pipe and four-pipe systems. The two-pipe system (Fig. 6-67) can solely be used for either heating or cooling, as the same hydronic circuit is used for both heating and cooling.

The changeover from heating to cooling mode takes place in the primary energy production plant. Problems may arise in this system in the transition time from heating to cooling mode and vice versa, because some rooms need to be heated while others need to be cooled at different loads.

**Three-pipe system**

The three-pipe system has a separate cold and hot water flow circuit and a joint return line. Although this solves the problem of simultaneous heating and cooling modes, it does waste energy. The reason for this is that the heating energy available in the joint return line has to be recooled in the refrigerator, and the cooling energy has to be reheated in the heat generator.

**Four-pipe system**

A neat solution for the problems described above is the four-pipe system with two separate hydronic circuits, one for heating and the other for cooling.
Fig. 6-67  Hydronic connection of a can coil, two-pipe system

1  Recirculated air
2  Supply air
3  Room air heating and cooling unit
5  Boiler
6  Water chiller
7  Changeover valve
6.7. Compact air conditioning units for individual rooms

Compact air conditioning units are designed for air conditioning an individual room, and are normally located directly in the relevant room. Their principal function is sensitive cooling of the ambient air. They are to a limited extent capable of dehumidification, heating and air filtering. Humidification is impossible. These units are thus "partial air conditioning units", equipped with all the necessary components, such as the compressor, evaporator, air or water-cooled condenser, fans and control elements as well as a control and safety unit.

They are supplied as ready-assembled units and thus also described as "plug-and-play" units. This group includes:

- Window air conditioning units
- Console air conditioning units
- Cabinet air conditioning units
- Split air conditioning units

6.7.1. Window air conditioning units

The unit is normally installed in an aperture in the window. "Through-the-wall"-installation is also an option.

The cooling capacity of these units ranges from 1 kW to 10 kW. Low capacity electric heating coils are available as auxiliary components. Mixing of the outside air is only possible to a limited extent. In window air conditioning units, capable of heating and cooling (heat pumps), the system is switched from heating to cooling mode by reversing the refrigerant flow by means of a four-way valve. This reverses the evaporator and condenser functions.

![Diagram of window air conditioning unit](source: Airwell)

**Fig. 6-68** Window air conditioning unit View from the inside of the room (source: Airwell)

<table>
<thead>
<tr>
<th>Number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Outside air</td>
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<tr>
<td>2</td>
<td>Exhaust air</td>
</tr>
<tr>
<td>3</td>
<td>Supply</td>
</tr>
<tr>
<td>4</td>
<td>Recirculated air</td>
</tr>
<tr>
<td>5</td>
<td>Fans</td>
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<tr>
<td>6</td>
<td>Evaporator</td>
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<td>Compressor</td>
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<tr>
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<td>Expansion valve</td>
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<td>Refrigerant line</td>
</tr>
<tr>
<td>11</td>
<td>Air filter</td>
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<td>Ventilation grid</td>
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<td>15</td>
<td>Window</td>
</tr>
<tr>
<td>16</td>
<td>Room</td>
</tr>
</tbody>
</table>

**Principle of operation**

The ambient air is drawn in by a fan, cooled and partially dehumidified in the evaporator. Then it is returned to the room via air discharge grid. The required proportion of outside air can be adjusted manually by means of an internal damper. A second fan draws in outside air to cool the condenser, and then discharges it back into the environment. The condensate from the ambient air which collects in the evaporator is either lead away into the environment, or sprayed on the condenser, where it evaporates.
The window air conditioning unit is thus a small compact refrigerating plant with a fully hermetic compressor and an air-cooled condenser. The thermodynamics of the refrigeration cycle are described in chapter 4 Refrigeration technology.

6.7.2. Console air conditioning units

This unit can either be installed permanently under a window in the room, or set on wheels. Console air conditioning units are available for the same capacity range as room air conditioning units. They fulfil the same functions and are subject to the same limitations.

Units with integrated air-cooled condensers can only be mounted on an external wall, as an opening in the wall is needed to supply the condenser with outside air. In mobile units, the air-cooled condenser is located on the outside with hoses to deliver the refrigerant to the console air conditioning unit. Units with water-cooled condensers can also be installed either as fixed hydronic connections or as portable units with a hose.

Electric or hot water heating coils can be installed as auxiliary components in these units. Console air conditioning units that are capable of heating and cooling are also available on the market. In these units the system changes from heating to cooling via four-way valve as well by reversing the direction of the refrigerant flow.

Fig. 6-69 Console air conditioning unit

1 Motor compressor
2 Operating capacitor
3 Copper-nickel-condenser
4 Low-/high-pressure control
5 Air filter
6 Evaporator
7 Room thermostat
8 Controller
9 Fan
10 Adjustable air outlet grid

6.7.3. Cabinet air conditioning units (with cooling)

As the term indicates, all the components of these units are accommodated in a cabinet-like housing. Cabinet air conditioning units are ready to connect, and available for a refrigeration capacity of 10 to 250 kW. For simple plants, these devices can be set up directly in the respective room that needs air conditioning and can discharge the air freely. However, they are usually installed in an adjacent room and connected to a duct system to avoid noise problems.

Electric air heating coils are available as auxiliary components, and humidification equipment can be fitted in the air duct. The fan is designed so that there is sufficient static pressure to overcome the air resistance resulting from a short low-velocity duct network. Cabinet air conditioning units are normally fitted with built-in water-cooled condensers. Variants with air-cooled condensers are also available. The air-cooled condenser is not fitted into the cabinet itself, but located out in the open as a separate unit.
Principle of operation

The principles are the same as with the console air conditioning unit.

![Diagram of a cabinet air conditioning unit](image)

**Fig. 6-70  Functioning design of a cabinet air conditioning unit**

1. Outdoor air
2. Exhaust air
3. Supply air
4. Recirculated air
5. Fan
6. Evaporator
7. Compressor
8. Condenser
9. Expansion valve
10. Refrigerant line
11. Housing
12. Ventilation grid
13. Damper
14. Air filter
15. Electric air heating coil
16. Exterior wall
17. Room

Application

Smaller cabinet air conditioning units can be used as individual room air conditioning units with or without a duct network. Larger units are normally used for a group of rooms. Typical examples of application are offices, shops etc.

A special version of these cabinet air conditioning units can be used to dehumidify the air in swimming pools. The recirculated air is first cooled and dehumidified respectively in the direct expansion evaporator and then reheated in the integrated air-cooled condenser.
6.7.4. Split air conditioning unit

Split air conditioning units consist of a refrigeration section comprising the compressor and the air-cooled condenser and an air handling section comprising the recirculated air fan and the direct expansion evaporator cooling coil. The refrigeration section may be located outside or in the plant room, while the air handling section can be designed as an individual room unit located in the room, or as a central cooling unit fitted to the duct network in the building. The two sections are linked together by the refrigerant lines.

Principle of operation

In functional terms, a split air conditioning unit basically consists of a refrigerant cycle with a compressor, an air-cooled condenser, an expansion valve and direct evaporator air cooling coil. If the cooling coil is also required to dehumidify the air, then a heating coil can be installed as an auxiliary component to act as a reheater in the recirculated air unit.

Split air conditioning units are available with refrigeration capacities from approximately 10 to 500 kW.

There are also split system solutions where one external unit operates several interior units (fan coils). These solutions are called VRV (variable refrigerant volume) or VRF (variable refrigerant flow) systems and operate a considerable number of rooms. It is also possible to cool rooms while other connected rooms have to be heated.

![Fig. 6-71 Structure of a split conditioning unit](source: Daikin)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>Multi-zone split system (source: Daikin)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Outdoor air (air inlet)</td>
<td>8 Condenser</td>
</tr>
<tr>
<td>2</td>
<td>Exhaust air (air outlet)</td>
<td>9 Expansion valve</td>
</tr>
<tr>
<td>3</td>
<td>Supply air</td>
<td>10 Refrigerant line</td>
</tr>
<tr>
<td>4</td>
<td>Recirculated air</td>
<td>11 Condenser set</td>
</tr>
<tr>
<td>5</td>
<td>Room</td>
<td>12 Fan coil unit</td>
</tr>
<tr>
<td>6</td>
<td>Evaporator</td>
<td>13 Ventilation grid</td>
</tr>
<tr>
<td>7</td>
<td>Compressor</td>
<td>14 Filter</td>
</tr>
</tbody>
</table>
6.8. Controlled home ventilation

In recent years, energy demand has fallen continuously in new buildings, due to the improved insulation and construction of the building envelope. As a result, ventilation losses represent an ever increasing proportion of the total heat demand.

Controlled home ventilation is mechanical ventilation for specified ventilation of apartments. It is segmented into decentralized and centralized ventilation. Depending on the equipment, a heat exchanger withdraws heat from the extract air and thus heats the supply air.

There are different kinds of systems of the controlled house ventilation. They are distinguished by type and principle of operation:

- **Type:**
  - Single unit
  - Central unit

- **Principle of operation**
  - Extract air system
  - Supply air system
  - Extract and supply air system
  - With heat recovery / without heat recovery
  - With heat pump

Consequences of a sealed building envelope

Looking at the development of the heating energy demand in residential and office buildings, we can see that improved construction of the building envelope (insulation, windows,…) reducing transmission losses) is the principal reason for the decrease in heat demand.

Ventilation heat losses represent a continually increasing proportion of the heat demand and is now often as large as the heat demand required for distribution.

A reduction in energy consumption – as specified in standards and regulations in various European countries – can be achieved with airtight windows and appropriately insulated brickwork. However, if safeguarding the required number of air changes is neglected, poor air quality becomes a serious problem, owing to humidity, radon, organic compounds, formaldehyde and other substances emitted by the building fabric, furniture and fittings etc.

This means on the one hand, a limitation of comfort for the residents and on the other hand, a risk of building damages, primarily caused by mold formation.

Controlled residential ventilation system

Window ventilation is not only inadequate for highly insulated buildings, but also undermines any attempt at saving energy. It is therefore vital to give serious consideration to installing a ventilation system. The ventilation heating demand can only be reduced without the potential damage caused by humidity by using a controlled residential ventilation system with heat recovery. Domestic comfort is improved by installing controlled residential ventilation:

- Disturbing noise from the outside is reduced (no open windows).
- The ambient air is filtered and thus free from dirt, dust, insects and pollen. It enters the rooms in a purified state. This is a great upside for allergy sufferers.
6.8.1. Controlled ventilation systems

Residential controlled ventilation systems can basically be classified as follows:

- Individual room units
- Individual ventilation units (for single living unit)
- Central ventilation units for multi-family dwellings

Energy efficiency

Controlled ventilation systems should always be fitted with a heat recovery system, as it is otherwise impossible to satisfy the demanded values (standards, regulations) applicable to the ventilation heating demand. The economical use of energy is equally important, and this cannot be achieved with three-phase motors. These units are therefore often fitted with direct current (DC) or electronically commutated (EC) motors.

Individual room units

Individual room units are installed directly on the external wall or window sill. They have the advantage of being easy to install, and supply the room with filtered outside air. The latter is preheated by utilizing the heat recovered from the extract air. The noise level associated with the individual unit is often seen as a drawback, and the fan is not very efficient from a mechanical point of view.

![Individual room supply and extract air units with heat recovery (unit) as per DIN 1946-6 (A.14)](image)

Individual ventilation systems

A separate ventilation system is installed for each apartment. The outside air is filtered and heated via heat recovery unit before being supplied to the living areas and bedrooms. The extract air is drawn through outlets in the bathrooms and toilets; this "stale" air flows from the living areas and bedrooms through vents in the doors or via special sound-insulated diffusers built into the ceilings. These systems often have 3-speed fans, allowing the user to adapt the supply air volume to their needs. Here, there is no problem with noise in living areas, because the ventilation unit itself can be installed in a location where it won't be a nuisance. The mechanical efficiency of the fans is often low.

Some individual ventilation units are also fitted with heat pumps. These can remove heat from the extract air and use it to heat the domestic hot water.
Central ventilation system for multi-family homes

In the case of central ventilation systems for multi-family homes, the air is conditioned centrally and then supplied to the individual residential units.

A certain amount of space is therefore required for the duct layout. Depending on how the heating costs are billed, it may also be necessary to install the heat recovery system locally, i.e. in individual residential units. This increases the complexity of the system and can lead to higher costs.

An advantage of this solution is that mechanically speaking, the fans are highly efficient.

Supply of outside air via ground heat exchangers

In buildings with centralized ventilation systems – but also for individual ventilation units – the outside air can be supplied via ground heat exchangers heat exchanger. The outside air is passed through pipes set into the ground. Thus, the outside air is slightly preheated in winter and slightly pre-cooled in summer, thereby providing minimal cooling which can be used for the living areas.

Maintenance

None of the domestic ventilation systems described above requires much maintenance, apart from the filters, which must be replaced regularly. This is something of a problem in practice, especially in the case of individual room units and individual systems, because not all users carry out this task regularly. In a central ventilation system, however, it can be done via plant operator.
7 Measuring and control technology and building automation (BA)

7.1. Introduction

This chapter is about measure and control technology as well as building automation technology, as the terms measuring and control technology and building automation (BA) already indicate. Due to the development of building automation by means of direct digital control systems, this subject has become increasingly important. An independent, interdisciplinary planning area imposes itself on measuring and control technology as well as building technology because of the level of development and market potential of building technology itself. This is why more and more consultants specialized in measuring and control technology or building automation are offering their services for the planning of control, regulation, management as well as optimization of energy consumption of entire building technology systems.

The connections between measurement and control technology and building automation are specified, among others, in the following norms:

- DIN IEC 60050-351
  International electrotechnical vocabulary - Part 351: Control technology
- EN 16484
  Building automation and control systems (BACS), parts 1-6
- EN 15232
  Energy performance of buildings
- …

Independent training program “Control technology in HVAC systems“

This chapter explains the basic definitions and functions of this subject. The graphs used herefore partially come from the independent study program “Control technology in HVAC systems” from Siemens Building Technologies.
7.2. Measuring point

The term ‘measuring technology’ defines the entirety of the process and the tools needed for the empirical analysis (measurement) of quantifiable elements in science and technology. The functions measuring technology are also to verify the adherence to dimensional tolerance, consumption metering, production control, as well as the general (in regards to measuring and control technology) control over technical processes by means of control according to units of measurement.

The history of measurement, when people first experimented with distance and time definition on to mechanical and electronical measuring equipment is a long and laborious path, interconnected with millennia of cultural history.

The precise measuring of physical quantities is very important in the era of building automation and facility management. The decision making concerning change or assertion of the energy consumption rate and maintenance costs for buildings is dependent on the preciseness of the measured data. In the control loop, it is important that the data logging is correct, so that the control results are precise and accurate. The choice of the right measuring equipment is significant for a correct measurement result. A correct (reliable) measurement result, in turn, is important for a meaningful evaluation.

The concepts of measuring technology are specified in the norms DIN 1319 and VDI/VDE 26000, part 2.

Base unit

A concise registry of measuring units was created by the International System of Units SI (Système International d’Unité):

<table>
<thead>
<tr>
<th>Quantity measured</th>
<th>SI base units</th>
<th>Name:</th>
<th>symbol:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>meter</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Mass</td>
<td>kilogram</td>
<td>kg</td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td>second</td>
<td>s</td>
<td></td>
</tr>
<tr>
<td>Electric current</td>
<td>ampere</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>Absolute temperature and difference in temperature</td>
<td>kelvin</td>
<td>K</td>
<td></td>
</tr>
<tr>
<td>Substance amount</td>
<td>mol</td>
<td>mol</td>
<td></td>
</tr>
<tr>
<td>Light intensity</td>
<td>candela</td>
<td>cd</td>
<td></td>
</tr>
</tbody>
</table>

Table 7-1 SI base units

Measuring means to measure a physical quantity (measuring unit) such as temperature, humidity, pressure, etc. with appropriate measuring equipment and to show it as a known unit or convert it into a standard signal DC 0…10 V, 0…20 mA. This standard signal can either be registered as a measured quantity on a data logger or displayed on a repeater panel or read in a data acquisition system.

Fig. 7-2 Basic process of measuring (Wheatstone bridge)

T Temperature sensor
R1 Measuring element (measured quantity)
Rj Resistor (compensation for lines loss)
D Measuring device (measuring equipment)
N Voltage source
7.3. Open-loop and closed-loop control

Open-loop and closed-loop controlling equipment both act on an object: It can be a plant, but it can also be a function or a data point.

The fundamental difference between open-loop control and closed-loop control is recognizable by the different response to disturbances occurring in the plant.

7.3.1. Comparison between open-loop and closed-loop control

**Open-loop control**

Open-loop control is a process in a system where one or more input variables influence one or more output variables according to a regularity defined for the specific application. There is no retroaction on the input variable. 

→ Open-loop control is an open chain of action.

**Closed-loop control**

Closed-loop control is a process in a system, where a physical variable (controlled variable) is continually measured, compared with a reference variable, and is influenced by an output variable in the sense of an adjustment.

→ Closed-loop control is a closed chain of action.

Example: Driving a car

![Fig. 7-3 Driving a car: Driver steers with covered view - No feedback.](image)

![Fig. 7-4 Driving a car: Driver acts as controller](image)

**Goals of open-loop control:**

The manipulated variable should be continually influenced by the value of the reference variable and defined specifications by means of a control.

The driver is not concentrating on the road. Thus, she does not adjust her course. The control variable (present direction of travel) is not adjusted to the reference variable (driver’s intended direction of travel).

**Goals of closed loop control:**

The controlled variable should be continually adjusted to the value of the reference variable (preferably without deviation).

The driver acts as a controller. She can now continually observe any errors in the direction of travel and correct them via the steering wheel. She is part of a closed-loop control process, so she also compensates for the effects of interference. Thus she corrects the car’s course (controlled variable) continually according to the desired driving direction (reference variable).
7.4. **Closed-loop control**

7.4.1. **Goals of a closed-loop control**

Closed-loop control is a process in a system, where a physical variable (controlled variable) is continually measured, compared with a reference variable, and is influenced by an output variable in the sense of an adjustment. Closed-loop control is a closed chain of action.

7.4.2. **Functions of a closed-loop control**

Closed-loop control is a continually repeated sequence of:

- Measurement of controlled variable \( x \)
- Comparison of controlled variable \( x \) with reference variable \( w \)
- Calculation of manipulated variable \( y \)
- Signalization of the manipulated variable \( y \)

7.4.3. **Control loop model**

A closed-loop control consists of one part controlled system and one part controlling equipment.

![Control loop model](image)

The control loop is formed by connecting the controlled system and controlling equipment in a closed chain of action.

The output of the controlled system is connected to the input of the controlling equipment, and the output of the controlling equipment to the input of the controlled system.

The control loop model is simply the abstract representation of the closed-loop control circuit.

The signal flow takes place in the loop (portrayal mostly clockwise).

Control loop function

The closed-loop control circuit enables the controlling equipment to act on the controlled system, and to specifically influence the controlled variable.
7.4.4. **Action diagram**

As in the open-loop control, there is a need for a concrete action diagram next to a control loop, so to recognize functional details.

The action diagram is created by refining the controlling equipment and controlled system with function blocks and the direction of control action.

The result is always aligned to an object:
- The plant diagram shows the controlled system.
- The function block diagram shows the controlling system.

The control loop elements are:
- Components or units for the plant
- Function blocks for the plant function.
Example 1, driving a car

![Image of a car with control loop model]

- **w**: drivers intended direction of travel
- **x**: actual direction of travel
- **y**: position of the steering wheel
- **z**: interferences such as cross winds, ...

**Control loop model**
- **w**: Reference variable w in the driver's head
- **x**: Actuator = hands on the steering wheel
- **y**: Control element = steering gear in the car
- **z**: Sensor = eyes of the driver

Example 2, manual control of a closed-loop room temperature control unit

![Image of a room with control loop model]

- **w**: desired room temperature
- **x**: observed room temperature (eyes)
- **y**: hand turning valve handle
- **z**: interferences such as solar intake

**Control loop model**
- **w**: Reference variable w in the room user's head
- **x**: Actuator = hand on the valve handle
- **y**: Control element = valve in the pipe
- **z**: Sensor = Eyes of the man

The user of the room compares controlled variable x (the current room temperature) with setpoint w (desired room temperature). If the controlled variable is too large, he closes the control element; if it is too small, he opens it.
7.4.5. Automatic closed-loop control

Goals of the automatic closed-loop control
The controller must be set such that both the response to setpoint changes and the response to interference of the control loop are stable, and that it compensates for such changes sufficiently quickly and without excessively large deflections.

Example: Automatic control of a room heating

![Fig. 7-10 Automatic control of a room heating](image)

Control loop model
Automatic control of a room heating

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>w</td>
<td>desired room temperature</td>
</tr>
<tr>
<td>x</td>
<td>actual (measured) room temperature</td>
</tr>
<tr>
<td>y_R</td>
<td>output signal of controller</td>
</tr>
<tr>
<td>z</td>
<td>interferences (e.g. solar intake, …)</td>
</tr>
<tr>
<td>T</td>
<td>temperature Sensor</td>
</tr>
<tr>
<td>M</td>
<td>actuator (motor)</td>
</tr>
</tbody>
</table>

In principle, a controller does the same thing as the person in the example above. The controller requires a sensor to detect the controlled variable, and an actuator to implement the manipulated variable at the control element.
7.5. **Building automation (BA)**

The term ‘building automation (BA)’ encompasses all facilities, processes, software and methods of automatic control and regulation, surveillance, optimization and operation as well as management of building technology services. Building automation is thus the central tool for a goal-oriented, energy efficient and safe operation of a building. The norm EN 15232 indicates which BA functions can contribute in what way, by means of energy efficiency classes.

Building automation systems such as these are installed in office buildings, shopping centers, hospitals, train stations, airports, etc., where complex technical building installations can influence each other and thus provide an opportunity to optimize their operation and energy usage. Modern building automation systems routinely use the most recent information from rooms and zones so to run the building technologic installations according to the specific needs. This is made possible as well as supported by the connection between the different automation stations as well as equipment with the standardized and open communications networks such as BACnet, KNX, and so on.

Fig. 7-11  Extensive technical equipment of a building with heating, cooling, lighting, shading, transport and security which are being operated efficiently and optimally with help of building automation solutions
Structure of a building automation system

A building automation system is structured hierarchically (see EN ISO 16484). The following three levels are differentiated:

- Management level
- Automation level
- Field level

![Fig. 7-12 The 3 levels of a building automation system](image)

**Management level**

The management level enables a supervisory operation and surveillance of an HVAC system, for example, or of different technical building installations (HVAC, lighting, shading, fire safety, security,…). For this purpose, the automation of different trades is integrated by means of standardized communication protocols.

The management level monitors and coordinates subordinate levels and systems and thus takes over functions such as:

- Operation and surveillance of different technical building installations
- Output of operation, fault and alarm signals
- Optimization of energy consumption across systems
- Accumulation of system data for further processing or transmission to third party systems
- Analysis and visualization of measuring and operation data
- …

**Automation level**

The automation level controls and monitors building technologic installations and works largely autonomously. It entails automation stations for central technical building installations as well as areas and rooms. It also includes facilities for operating and monitoring installations, areas and rooms.

These automation stations are interconnected, which enables the exchange of data (e.g.: shared use of measured data) but also the use of universal optimization functions on this level.

The hardware of the automation level is either a compact design for standardized use or allows for process instruments to be combined with modular input/output modules (I/O modules) so to reach a plant specific solution.

The input/output modules (or the integrated in- and outputs) form the communication interface between automation stations and measuring device, actuator and signal unit in the installations, areas and rooms (see field level).
Binary signals (in/out, 1/0, high/low) can be directly processed, while analogue signals (electrical resistance, voltage or power) have to be converted into digital signals by means of so-called A/D converter (analogue/digital), so that the automation station can process them. Commands and values of the automation stations also need to be converted according to the signals of the installations (D/A converter).

The main functions of the automation system are as follows:
- measure, control
- switch, report, count
- optimize
- monitor
- operate

Field level
The field level encompasses the measuring, placement, switching and reporting devices of building technologic installations. Sensors register current operating conditions which can be modified by means of actuators in technical building installations:
- recording of measured values such as temperature, humidity, air quality, pressure, volume flow or meter pulse (sensors)
- switching of motors, lighting and shading elements as well as other units (actuators)
- reporting of the switch setting from the monitoring units (sensors)
- setting of the valve and damper actuators (actuators)

Part of the field level are also the measuring, placement, switching and reporting devices of the technical building installations in rooms and areas such as:
- radiator valve
- hot and cold water valve in fan coils and heating/cooling elements
- volume flow controller in VAV systems
- ballast from lighting systems
- motor of shading systems
- room sensor for temperature, humidity, air quality, …
- room control elements such as switch for lighting or shading, setpoint adjuster, …
- room control elements which combine different control elements
- …

Standardized communication systems
A building automation system can operate a multitude of control loops, remote-control reference variables or retrieve manipulated variables. With this, it can determine the overall load condition of the HVAC plants as well as in the rooms and areas via demand-based operation of the heat and cooling generators.

The data exchange within the building automation systems takes place in standardized communication networks, whereby different communication protocols are chosen according to system size, needed transmission speed, expandability or operating safety.

The following principles apply for data exchange
- the data exchange can take place either horizontally (inside a level) or vertically (in-between the levels)
- each level works with the data specifically assigned to them
- data, which is transmitted to higher levels is to be reduced respectively condensed to its essentials

An overload of a level, which would consequently lead to a longer processing and reaction time, with the data of another can be avoided as long as these principles are abided by.
Demands on the communication systems in building automation:

- transmission of simple events up to complex data structures
- integration of similar and different trades on the level of the greatest use
- utilizing existing infrastructure (LAN,WAN) of the customer
- central operation and surveillance, but with local flexibility
- reduction of the installation, operating and service costs
- efficient interconnectivity of a large number of stations across great distances
- flexibility of installation technology
- ....

These demands can only be met with standardized communication systems. Different systems are needed so to cover those requirements.

Many data exchange and communication systems are available these days. The following overview shows the most important communication protocols, which are supported and used in Siemens System Solutions (e.g.: Desigo). The communication protocols of the automation and management levels are standardized according to different EN-norms here. The communication protocols, which harness and embed the equipments and products on field level are mostly industry standards, which were established for different fields of application over time, e.g.: M-Bus for meter, DALI for lighting groups...

Fig. 7-13 Standardized communication systems in Siemens System Solutions
When building technology creates perfect places –
that's Ingenuity for life.

Never too cold. Never too warm.
Always safe. Always secure.

With our knowledge and technology, our products,
our solutions and our services, we turn places into
perfect places.

We create perfect places for their users’ needs –
for every stage of life.

#CreatingPerfectPlaces
siemens.com/perfect-places