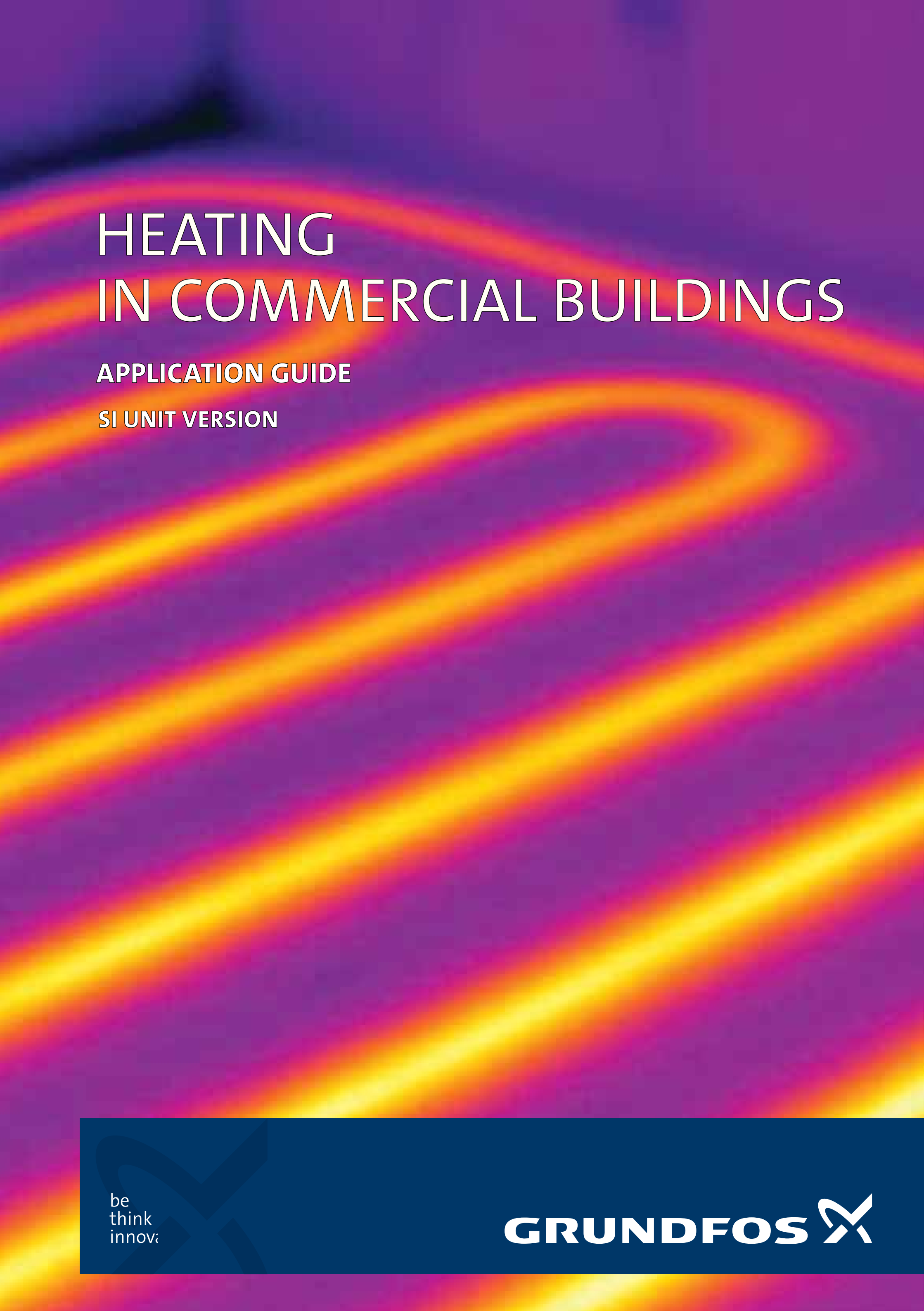

HEATING IN COMMERCIAL BUILDINGS

APPLICATION GUIDE

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PREFACE

Throughout the history of mankind, fire has played an essential role as provider of warmth and comfort and thus it has secured the development and evolution of the human being. Today – hundreds of years later – the ability to find shelter and stay warm is still one of the most fundamental needs of human beings and the main purpose of modern buildings around the world. However, much has changed since the early attempts with fire and we now know the importance of, not only keeping warm and dry, but also to facilitate the optimum indoor climate in order to attain maximum productivity and minimize energy consumption.
Due to recent year's continuous focus on climate change and scarcity of energy resources, continuously tightened restrictions on energy consumption have been agreed in most parts of the world. However, energy consumption in buildings still represents around 40 % of the total consumption in society, leaving a huge potential for improvements. Rising energy prices and the constant concern of environmental impact keep pushing the development towards better energy efficiency and new solutions. However, as the construction industry is often characterised by conservatism and short term investments, the solutions that provide the best comfort and productivity may sometimes be neglected and disregarded with arguments like "don't change what already works" and "it's too expensive and unnecessary". But the solution may not be that difficult after all, often an improved indoor environment will pay off in the long run as productivity and employee satisfaction increases.
The scope of this application guide is to define and clarify the purpose of the heating application and the reason why it should be taken seriously as well as outline the necessity of energy efficient systems. It is not a complete guideline and it will not substitute the numerous standards in this area, but we hope that it will serve as a source of inspiration and maybe challenge the way the heating application is normally dealt with.

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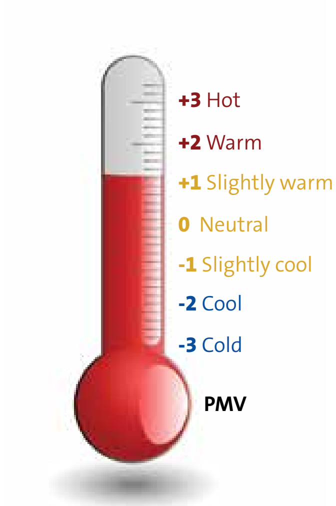
WHY DO WE HEAT?

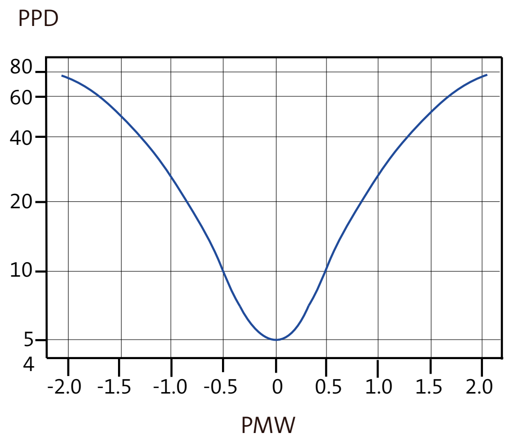
The main reason for heating buildings is to shelter against the colder environment and to ensure an adequate level of thermal comfort in a building. But how do we define thermal comfort and why should we care about it? These issues are defined and discussed in the following chapter.

Thermal comfort

Thermal comfort is a subjective condition or perception of the thermal environment. It has to do with surrounding temperatures and heat sources in relation to thermal sensation of the human being.
We heat buildings to feel comfortable, which not only highly affects our level of wellbeing but also our productivity and learning capacity as described in a later section. This means that the temperature range should be calibrated to the work carried out – e.g. studies show that humans are most productive in offices where the air temperature is a bit lower than what most people find a "neutral" temperature. If the temperature is either raised or lowered from this optimum value, the productivity quickly falls and the percentage of dissatisfied people rises, respectively. However, thermal comfort is very individual and it is never possible to obtain 100 % satisfaction. According to International Standard ISO 7730 – which forms the basis for both ASHRAE and European EN standards – the percentage of dissatisfied people reaches a minimum at around 5 %, meaning that some people always will be dissatisfied with the indoor environment no matter how well controlled it is.
An often used tool to deal with thermal comfort is the so-called Predicted Mean Vote (PMV),



Thermal sensation scale for the Predicted Mean Vote (PMV)



The Predicted Percentage of Dissatisfied, (PPD) as a function of the Predicted Mean Vote, (PMV)

which is a measure of the wellbeing of the humans in a given thermal environment. It is a prediction of the mean value of the votes of a large group of people on the 7-point thermal sensation scale. The optimal thermal environment corresponds to PMV = 0 (neutral perception).
Based on the PMV index it is possible to predict the general level of dissatisfaction amongst people by calculating the Predicted Percentage of Dissatisfied (PPD) index. The relationship between PMV and PPD appears on the graph.

The ISO 7730 standard divides the level of comfort into three comfort categories; A, B and C or I, II and III with category A being the best class with less than 6 % dissatisfied and thereby also the highest productivity. Some standards, e.g. the European EN 15251, further include a fourth comfort level, D or IV.

The PMV and PPD express warm and cold discomfort for the body as a whole, but thermal dissatisfaction can also be caused by unwanted cooling or heating of one particular part of the

USAGE OF APPLIANCES

Comfort category	PPD-index (Predicted Percentage of Dissatisfied)	PMV-index (Predicted Mean Vote)	Applicability
A (I)	< 6 %	-0.2 < PMV < +0.2	Sensitive and fragile persons like handicapped, sick, young children and elderly people etc.
B (II)	< 10 %	-0.5 < PMV < +0.5	Normal standard for new buildings and renovations
C (III)	< 15 %	-0.7 < PMV < +0.7	Low standard for existing buildings
D (IV)	> 15 %	PMV < -0.7 or +0.7 < PMV	Should only be accepted for very short periods of the year

Comfort categories describing the thermal environment in accordance with International Standard ISO 7730 and EN 15251.

body. This is known as local thermal discomfort. The most common cause of local discomfort is draught; however, too high vertical temperature gradients, too warm or cool floors or a too high radiant temperature asymmetry from surfaces may also be sources of local discomfort. Local thermal discomfort is mainly a problem for people at light sedentary activity, as people become more thermally sensible at lower levels of activity.
To maintain a given comfort category e.g. category B with less than 10 % dissatisfied people, a set of criteria is given for the design of the heating (and cooling) systems. These conditions are specified in standards or given by the building owner. By designing the HVAC installations based on the thermal comfort indices PMV-PPD instead of only air temperature as the design criterion, the effect on air velocities will be taken into account, ensuring both overall and local thermal comfort.

Commercial buildings under construction

Example: Sizing parameters based on thermal comfort classes

A building owner wants his new office building to uphold an indoor environment corresponding to comfort category A, giving him less than 6 % dissatisfied employees and high productivity, potentially saving him money. Based on International Standard ISO 7730, the HVAC engineers translate this demand into a set of manageable sizing criteria for the heating system.

Operative temperature:	**22.0 +/- 1.0 (winter) and 24.5 +/- 1.0 (summer)**
Maximum mean air velocity:	**0.10 m/s (winter) and 0.12 m/s (summer)**
Vertical air temperature difference:	**< 2 °C**
Range of floor temperature:	**19-29 °C**
Radiant asymmetry caused by	
• warm/cool ceilings:	**< 5 °C / < 14 °C**
• warm/cool walls:	**< 23 °C / < 10 °C**

Based on these criteria, it is possible to design a good heating system that will ensure the desired level of comfort.

A good indoor climate improves working efficiency, satisfaction level and health

Performance of work

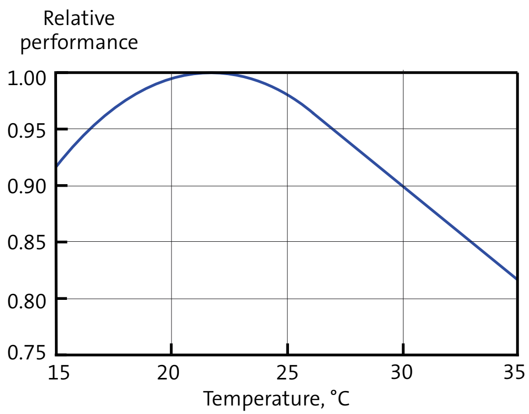
The performance is - as mentioned above – highly affected by the thermal environment. It has been proven by Wyon and Wargocki (2006) and published in REHVA Guidebook 6 that

- Thermal discomfort distracts attention and generates complaints that increase maintenance costs
- Warmth reduce mental capabilities and exacerbates Sick Building Syndrome (SBS) symptoms
- Cold conditions lower finger temperatures and have a negative effect on mental dexterity
- Rapid temperature swings have the same effects on office work as slightly raised room temperatures, while slow temperature swings just cause discomfort
- Thermal discomfort can reduce performance by 5-15 %

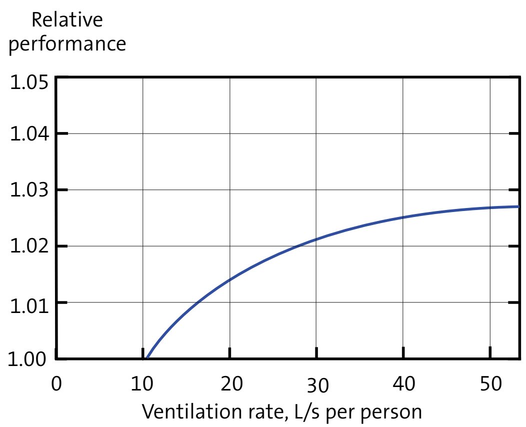
From the figures to the right it is seen how the performance of work is affected by the room temperature.
However, performance is also highly affected by air quality and ventilation rates. This relationship is illustrated by the figure below.
The figures clearly shows how an increment in ventilation rate may increase the performance but also that this gain flattens out at some point. Thermal comfort and indoor air quality is closely related and it is difficult to separate the two of them.

“But what about the economy? Isn’t it expensive to ensure a good indoor environment?”

No quick answers may be given and the question should instead be answered by looking at the problem from another point of view. Salaries continue to constitute the bulk of total building



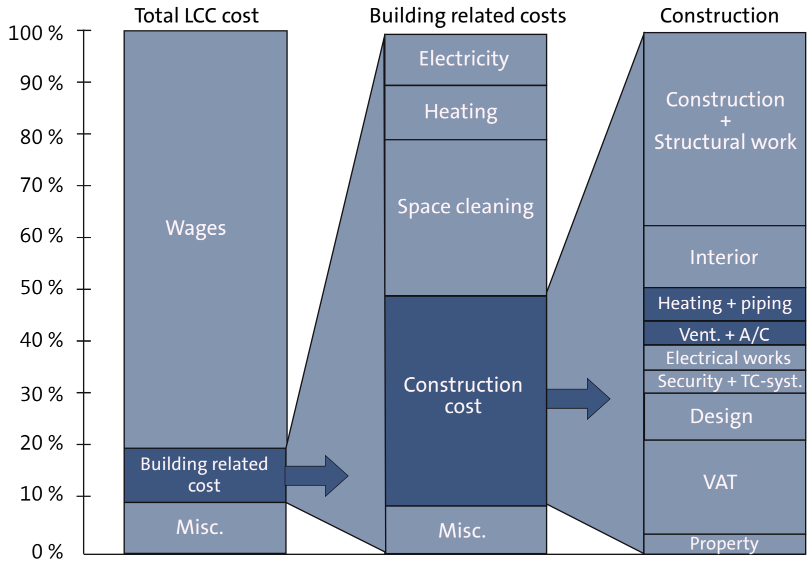
Relative performance as a function of temperature (REHVA Guidebook 6).The curve is based on measured work performance from 24 studies. In these studies the optimal working temperature is 22 °C. It suggests a reduction of performance of approximately 1% for every 1% decrease or increase of temperature



Relative performance as a function of ventilation rate (REHVA Guidebook 6). Effect of increasing ventilation rate in relation to a reference ventilation rate of 10 l/s per person. In this case it is possible to raise the performance by approximately 3 % by increasing the ventilation rate.

costs in its lifetime and therefore enormous savings may be achieved by creating the optimum indoor environment as it will increase the performance and efficiency of work. Investments in HVAC installations represent around 0.4 % of the total LCC-budget whereas salaries make up around 80 % (see figure below). In this case even the slightest add-on investment in IEQ (Indoor Environment Quality)-improving technologies should be welcomed. Imagine if an extra 10 % investment in HVAC systems would increase the staff productivity of just 2 %.

From these conclusions it is evident that thermal comfort plays a vital role in attaining a good work environment and that employers and building owner should pay special attention when specifying the building’s HVAC systems, which have a great impact on the buildings IEQ. Even the slightest reduction in IEQ will result in comprehensive productivity loss because the investments in the building, building services and equipment are relatively small in relation to the huge costs for salaries.



Relative significance of salary cost for a typical office building (REHVA Guidebook 6).

EFFICIENT HEATING

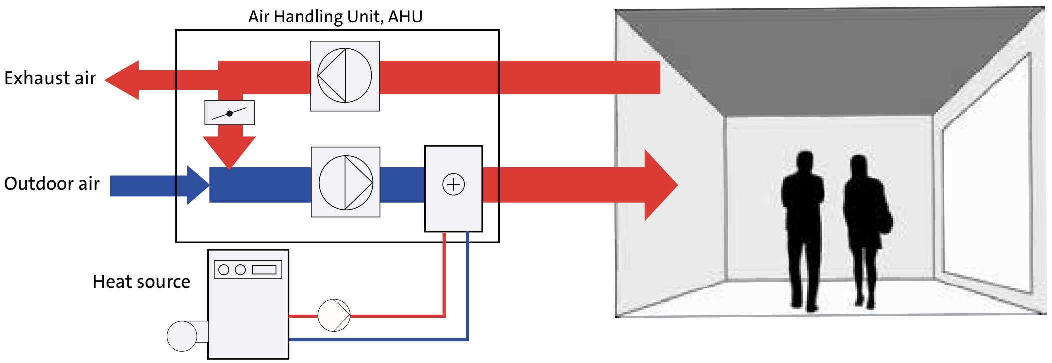
With the rapidly increasing demand for energy efficient heating solutions in combination with a high degree of comfort and outstanding indoor environment, it is needed to take a broad view on the building and the way it is heated. A very important issue that has to be dealt with is whether an air-based or a hydronic system should be used. This choice will have a long term effect on the operation cost of the building.

Air-based vs. hydronic systems

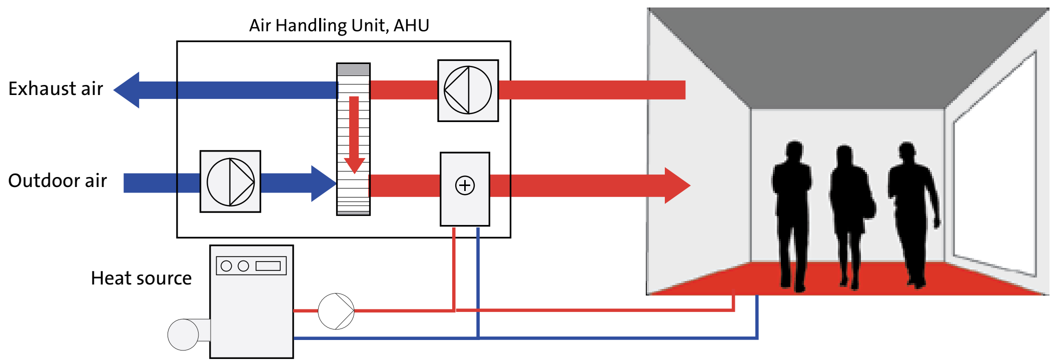
At some point in the heating system, energy in terms of heat has to change medium to mix with room air. The heat exchange from water to air normally takes place once regardless of the system type. However, where these heat exchanging mechanisms in an air-based system take place in the heating coils of e.g. the air handling unit (AHU), water-based systems wait until the very last moment. Here the heat exchange typically takes place in the very room, where the heating is needed – e.g. radiators release the energy to the room air. The main difference between the two systems is the way the heat energy is transported and released to the room air– either through the ventilation system or by a dedicated hydronic system.

Forced air systems are all-air systems where large amounts of air are used in order to condition the space. The air volume clearly exceeds the need for ventilation in the room, because the air is not only used for ventilation but as a primary heat medium as well. In order to reduce the amount of cold outdoor air to be heated, an air recirculation duct is introduced. This means that a large amount of polluted air is re-injected to the space.
If the air volume was based on the need for ventilation alone, the air volume would be reduced significantly.

In order to reduce the needed air volume, hydronic heating systems may be introduced to the building. Hydronic systems work very well together with dedicated outdoor air systems (DOAS). In this situation the air handler is used for ventilation within the space alone and not for heating, which is taken care of by the hydronic system. In this case, the air is supplied to the space at what is called isothermal conditions; meaning that the inlet temperature and room temperature are more or less equal or at temperatures just a few degrees higher. When working in parallel the hydronic system and the ventilation system usually will improve IEQ as well as reduce energy consumption both for heat production and distribution.



Forced air system used for space heating and ventilation. Here large amounts of air are needed. In order to save energy for heating of large air amounts a recirculation damper is introduced. It allows stale air from the space to be re-injected.



Dedicated Outdoor Air System (DOAS) used for space ventilation. Here the air volume is adapted to what is needed for IAQ alone. Here a rotary heat exchanger is introduced. This exchanger may recover up to approximately 90% of the heat energy in the stale air. The return of investment in a rotary heat exchanger may be counted in weeks or month. If further space heating is needed, the floor heating system is activated.

Energy distribution cost

The discussion whether air-based systems or hydronic systems is the best is old but nonetheless important. Air-based conditioning systems still represent a major part of the heating systems around the world, but why is that? “Are air-based systems really the best solution giving the highest energy efficiency?”
The answer is no! This is seen when simply analysing the heat capacity of the two media, water and air. The largest difference between these two media is the heat capacity and density. Where air has a specific heat capacity (c_p) of approximately 1.0 kJ/kg K, water will carry around 420 % more energy per kilogram due to a larger specific heat capacity of around 4.2 kJ/kg K. Moreover, the density of water is approximately 800 times higher than the one of air. 1000 kg/m^3 and 1,2 kg/m^3 respectively. Together this gives water a volumetric heat capacity (VHC = specific heat x density) that is almost 3,500 % higher for water than air, meaning that water will carry 3,500 times more energy per m^3 than air. It is evident that much more space for ducts under e.g. false ceilings is needed to transport heat by air. For example, a 32 mm hydronic pipe will carry the same amount of energy as a 500 mm circular air duct. This fact alone should give designers second thoughts about using air as transportation medium for energy. Moreover, the cost of energy transportation is way higher for air-based systems as outlined in the example.

Example: Impact of low delta-T (ΔT) syndrome 1

50 kW heat needs to be transported through a duct/pipe at a temperature difference of 10 °C. How much energy does it cost to distribute it with air and water as medium, respectively?

Energy consumption when using air:
Volumetric flow, Q_{air} = 50 kW/(1.2 kg/m^3 x 1.0 kJ/kg K x 10 K) = 4.2 m^3/s = 15,000 m^3/h
Fan pressure, Δp_{fan} = 1.5 kPa = 1.5 kJ/m^3
Fan efficiency (global), η_{fan} = 0.55
Power consumption in fan, P_{fan} = (4.2 m^3/s x 1.5 kJ/m^3) / 0.55 = 11.4 kW

Energy consumption when using water:
Volumetric flow, Q_{water} = 50 kW/(1000.0 kg/m^3 x 4.2 kJ/kg K x 10 K) = 0.001 m^3/s = 4.3 m^3/h
Pump pressure, Δp_{pump} = 200 kPa = 200 kJ/m^3
Pump efficiency (global) , η_{pump} = 0.55
Power consumption in pump, P_{pump} = (0.001 m^3/s x 200 kJ/m^3) / 0.55 = 0.4 kW

Relative deviation
(11.4-0.4)/0.4 x 100% = 2,750 %

Besides the much bigger ducts necessary when using air as medium instead of water, the example shows how it is around 27 times more expensive to transport heat through a ventilation system than through a hydronic system, when operating with the same temperature difference and overall fan/pump efficiency.

In normal HVAC applications, however, the temperature difference in hydronic systems is much bigger than those in air-based systems – it is normal to have temperature differences up to around 40-45 °C. Taking these temperature differences into account, the relative deviation between hydronic and air-based systems become higher than 10,000 %, making hydronic systems more than 100 times more efficient in terms of energy distribution costs.

Indoor environmental quality

"What about the indoor environment, surely a water-based hydronic radiator system cannot give the same level of comfort and environmental quality as an air-based ventilation system?"

Again, the answer is clear – yes it can! The use of hydronic systems often enables both a better thermal and acoustic comfort with the main reason being that they are not relying on large supplies of air. The ventilation system only has to provide enough air to ensure an adequate indoor air quality (IAQ) meaning that the supply air is not used for heating thus lowering the air change rate. This has several benefits.

First and foremost, a reduced ventilation rate results in lower air velocities in the room. This is one of the biggest advantages of using hydronic systems as thermal comfort is highly affected by air velocities as it may lead to draught (unwanted local cooling of body parts as a result of air movement). From the table, an example of the maximum allowed air velocity in the occupied zone is given for the different comfort categories at sedentary activity.

Reduced ventilation rates and thus reduced air velocities result in a better thermal environment. As the example shows, by halving the maximum mean air velocity from 0.21 to 0.10 m/s, it is possible to increase the local thermal comfort in relation to draught from category C to A.
Besides the issue of air velocity, it is possible to supply a room with much more heat by using e.g. radiators than by ventilation as heat from radiators is emitted by both convection and radiation resulting in a more even thermal sensation.

Activity	Comfort Category	Max. mean air velocity (heating season)
Sedentary activity, 1.2 met. (Office, dwelling, school etc.)	A	0.10 m/s
	B	0.16 m/s
	C	0.21 m/s

Example of the maximum allowed mean air velocity for sedentary activity. The values are based on a turbulence intensity of 40 % and air inlet temperature equal to the operative temperature of 22 °C.

Air diffusors suppliying high air flow rates contribute to what is often regarded as a high noise office environment.

Finally, high ventilation rates introduce the risk of noise from the duct network and air diffusers in the ceiling. It is obvious that noise should be avoided as it may distract attention and thereby reduce productivity.

As described earlier, thermal discomfort generates complaints and may in some cases reduce the working performance with up to 15 %. With this conclusion in mind and the possibility of noise, hydronic systems are most often superior compared to air-based systems when it comes to IEQ. In addition to this, it is often much easier to design a well-functioning hydronic heat emitting system than an air-based system giving the same level of comfort and IEQ.

Low temperature heating

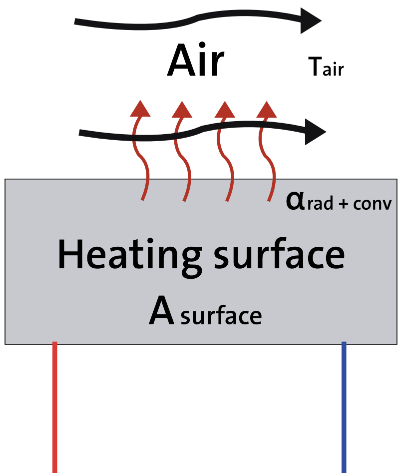
The process of heat transfer may be expressed as the flow of thermal energy from high to low temperature regions. In every transfer process in a heating system, energy is wasted and lost to the surroundings resulting in continuously decreasing temperatures. That is why it is needed to supply heating systems with higher temperatures than needed at the end-user, e.g. room air. It has for many years been common to construct systems with supply temperatures between 70-90 °C, even though the aim only is to have room air temperatures at around 22 °C. However, it is relatively expensive to achieve such relatively high temperatures.

The heat transferring process from a surface – e.g. a heating coil or radiator – to the surrounding air may be expressed as a function of a combined heat transfer coefficient, the surface area and mean temperature difference between surface and air.

$\Phi = \alpha \times A \times (t_s - t_a)$ where

Φ = Heat flow [kW]
α = Surface heat transmission coefficient [W/m²K]
A = Surface area [m²]
t_s = Surface temperature [°C]
t_a = Air temperature [°C]

When using air-based heating systems, air is supplied to the space at a higher temperature than the room air temperature. The difference can be as high as 8 °C to 10 °C. The heating of the supply air takes place in the heating coils which normally is located in the air handler (AHU). Due to cost reasons the size of the air handler and coils are limited, thereby limiting the heating coil surface area. This means that the temperature difference between coil surface and air has to be proportionally bigger, requiring a higher water supply temperature for the coil. By utilizing a much bigger surface area as in e.g. underfloor heating, it is possible to reduce the water supply temperature drastically. However, heating coils in AHU´s are still needed but only for conditioning of cool outdoor air in order to achieve isothermal conditions of the supply air.



Schematic illustration of the heat transfer from a heating surface to surrounding air

Example: Low temperature heating

5 kW heat needs to be delivered to a 200 m² room with air temperature 22 °C from an underfloor heating system. This corresponds to 25 W m² floor.

Underfloor heating system (pipes cast into screed)
Pipe diameter and spacing = ø20 mm (pipe spacing = 150 mm)
Screed thickness = 150 mm (concrete, λ = 1.9 W/mK)
Floor covering = light carpet (R = 0.1 m²K/W)
Maximum temperature difference of water in pipes, ΔT_{water} = 5 °C (limited due to thermal comfort)

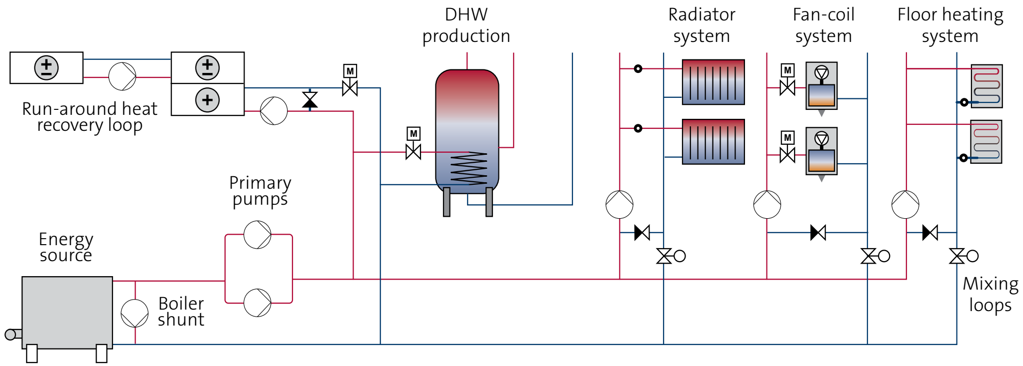
Heat transfer coefficient (α) is determined in accordance with European Standard EN 1264-2:2008 and REHVA Guidebook 7 to 2.57 W/m²K. This is based on geometry and materials used.

$\Delta T_{log} = \Phi / (\alpha \times A)$ = 5,000 W/(2.57 W/m²K x 200 m²) = 9.7 °C (maximum allowed difference is 33 °C)
$T_{supply} = \Delta T_{log} + T_{air} + \Delta T_{water}/2$ = 9.7 °C + 22 °C + 2.5 °C = 34.2 °C
$T_{return} = T_{supply} - \Delta T_{water}$ = 34.2 °C - 5 °C = 29.2 °C
Circulated water = $\Phi / (c_p \times \Delta T_{water})$ = 5,000 W/ (4,200 J/kgK x 5 K) = 0.24 kg/s

As shown it is possible to supply heat at a much lower water supply temperature (34.2 °C) in an underfloor heating system than is the case with a traditional air-based system (approx. 70 °C). The capacity of the underfloor heating system is much higher than what is shown in this example potentially delivering up to maximum 100 W/ m² floor and still ensuring thermal comfort resulting in a supply water temperature of only 55 °C.

HEATING SYSTEMS

In the following the heating system and its different sub-systems and control mechanisms are described.



Schematic illustration of a central heating system with its main components.

Heat production

In commercial building's heating is typically produced, centrally within the building (or on the buildings premises) or the building is connected to a district heating network. Production of on-site central heating takes place with different technologies – below the most common and often used solutions are described.

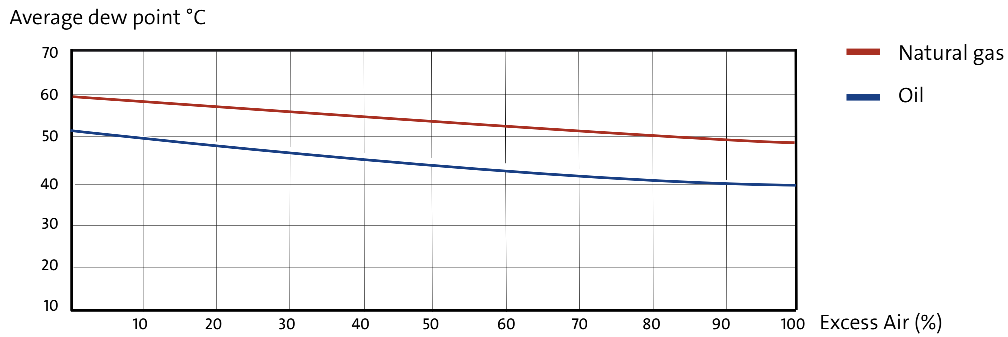
Gas and oil boilers

Boilers or furnaces are the traditional closed vessel used to heat water or other fluids to be used in central heating applications. A boiler installation has the following components: burner, nozzles, boiler casing, hot-water tank (integrated or separate) and a chimney. The boiler generates heat from combustion of domestic fuel oil (smaller systems), heavy fuel oil (larger systems), and natural gas. Solid fuel boilers are not discussed in this publication.

Exeample of a condensing boiler. Courtesy of Viessmann.

The condensing boiler

Conventionally, the energy in the hot gasses produced by the combustion process is exchanged with the separately circulating water medium thus raising the temperature of it. Modern condensing boilers are more efficient as they also utilize the latent heat in the vaporized water in the flue gasses.
Standard boilers reach a maximum thermal efficiency around 80 %. This means that close to 20 % of the heat generated by standard boilers is lost with the flue. Much of this heat is in the form of water that has been vaporized during combustion. By condensing this water vapor on the boiler's heat exchanger, the extra energy carried by the vapor is released back to the boiler as useful heat. The water vapour condensate is used to pre-heat the return circulating water and thereby lowering the flue gas temperature from typically 120-180 °C to only 50-60 °C. Condensing boilers commonly achieve high thermal efficiencies of 90-98 %.
To withstand the corrosive effects of acidic condensate, high efficiency boilers must use stainless steel or other corrosion-resistant heat exchangers.

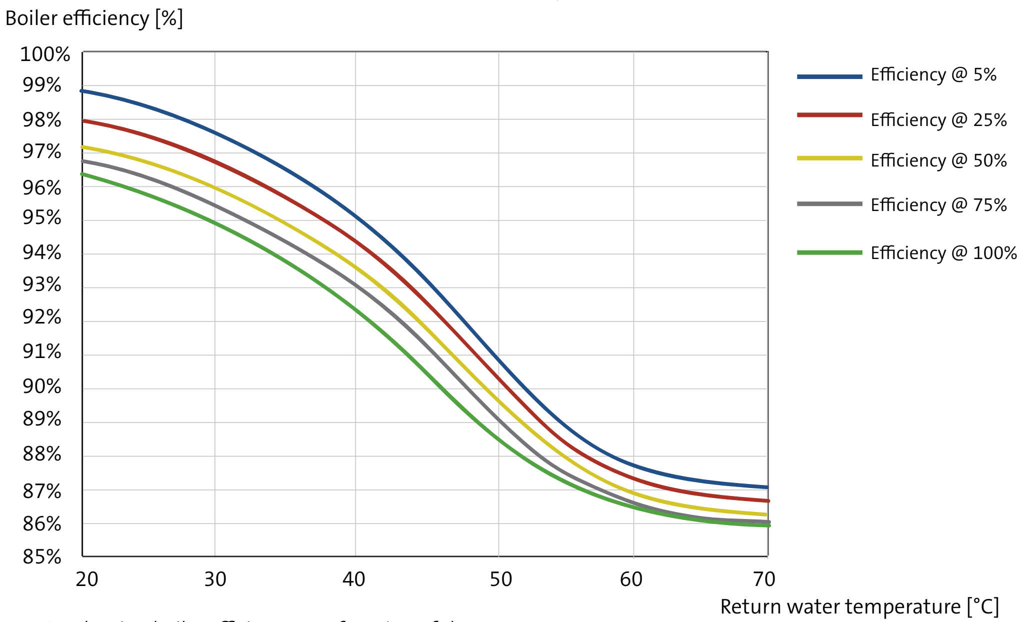


Average dew point for typical fuels. Excess air - the ratio of the quantity of supplied air to the consumption process above that theoretically necessary for perfect combustion.

Return-water temperature

To achieve maximum efficiency, condensing boilers must be able to achieve condensation of exhaust gas on the heat exchanger. To do this, the circulating water's temperature upon return to the boiler must be as cool as possible. The cooler the returning water, the greater the rate of condensation and the higher the efficiency of the boiler. Peak efficiency is achieved when return water temperatures are as low as 25 – 27 °C. This demands low-temperature applications such as in-floor radiant heat. Efficiency declines dramatically as return water temperatures rise beyond 58- 60 °C, because little condensation is possible above this temperature.

Because of the larger and more efficient heat exchanger on the condensing boiler this will always be more efficient than standard boilers, and not only when running in condensing mode.



Condensing boiler efficiency as a function of the return water temperature

Example: Fuel consumption with or without condensation

A 1500 kW heating system is supplied by a natural gas fired condensing boiler. In the following example, fuel consumption at peak load is calculated in different situations. The system is investigated for both 90 °C and 70 °C flow temperatures and for return water temperatures 10 °C, 20 °C and maximum 30 °C lower than the supply.

Energy content in natural gas: 10.8 kWh/m^3

Gas consumption, V = (1500 kW/10.8 kWh/m^3)/η

90 °C flow temperature			
Temperature difference, Δt	10 °C	20 °C	30 °C
Return temperature, t_R	80° C	70 °C	60 °C
Boiler efficiency, η	86,5 %	87,0 %	87,5 °C
Gas consumption, V	**160.6 m³/h**	**159.6 m³/h**	**158.7 m³/h**
70 °C flow temperature			
Temperature difference, Δt	10 °C	20 °C	30 °C
Return temperature, t_R	60 °C	50 °C	40 °C
Boiler efficiency, η	87,5 %	94,5 %	96 %
Gas consumption, V	**158.7 m³/h**	**147.0 m³/h**	**144.7 m³/h**

When designing the heating system it is very important to secure as low return temperatures as possible in order to reduce energy consumption. Approximately 10 % fuel may be saved by designing a low-temperature system with a return temperature of 40 °C instead of 80 °C.

Boiler shunt

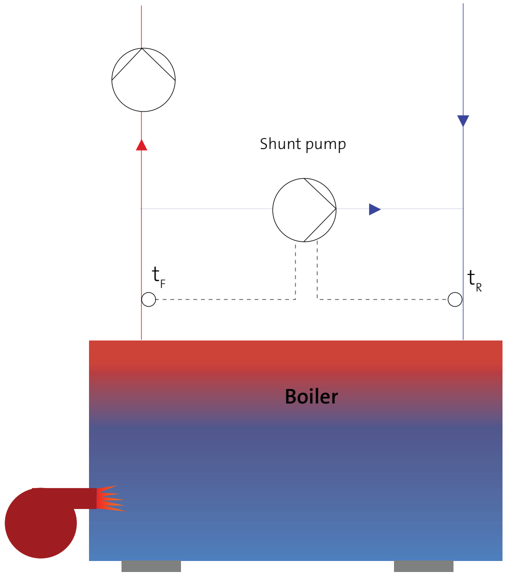
A boiler shunt is often the first of many temperature control mechanisms that the fluid undergoes in the distribution system from supply to final emission. The purpose of the shunt is twofold:

- To mix return water with part of the supply water and in that way ensure a certain minimum return pipe temperature to the boiler as too large temperature differences (t_F - t_R) cause mechanical stress in the boiler material and thus reduce the life of it.
- To avoid condensation and corrosion inside the boiler by keeping the return water temperature (t_R) above the flue gas dew point temperature.

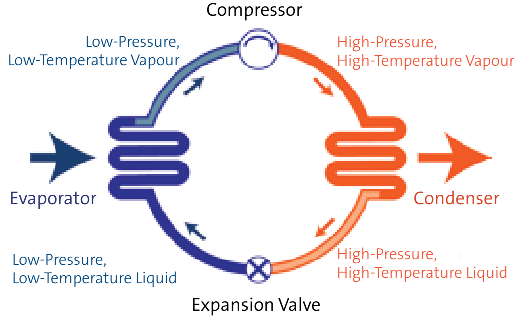
However, modern smart pumping technology now makes it possible to obtain the most efficient control and operation of the boiler shunt application by implementing temperature-controlled smart pumps, which continuously adjust the return water temperature to the optimum value based on measurements of supply and return water temperature.

Heat pumps

By means of a circulating refrigerant, heat pumps are devices that transfer energy from one temperature level to another in order to utilize low temperature heat sources. However, heat pumps are found in many different HVAC applications and if used in air-conditioning or refrigeration, the process is turned around, transferring heat from a high temperature level to a low level.

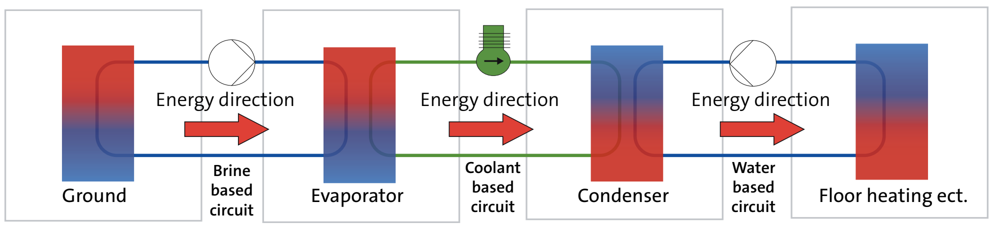


Boiler with a shunt bypass between flow and return. Here a speed controlled pump should be used. The pump performance is based on the temperature difference between flow and return. If the temperature difference exceeds for example 30 °C, the pump ramps up and vice versa.



The heat pump refrigeration cycle. In the evaporator the energy is collected from an external environment. In the condenser the heat distribution takes place.

Heat pumps exploit the physical properties of the volatile evaporating and condensing refrigerant. The refrigerant, in its gaseous state, is pressurized and circulated through the system by a compressor. On the discharge side of the compressor, now hot and highly pressurized vapor is cooled in a heat exchanger, the condenser, until it condenses into a high pressure, moderate temperature liquid. The condensed refrigerant then passes through a pressure-lowering expansion valve. The low pressure liquid refrigerant then enters another heat exchanger, the evaporator, in which the fluid absorbs heat and boils. After that the vaporized refrigerant returns to the compressor and the cycle is repeated.
Heat sources to be connected with the evaporator often include the outside air, as used in an air-source heat pump (ASHP). However, larger systems may benefit from using water-based heat sources instead, as water contains heat in a much denser form than air.



Schematic showing the circuits in a Ground Source Heat Pump system (GSHP).

Heat pumps are characterized by using less energy than other heating plants because they only need electricity to drive the compressor in the refrigeration loop. In heat pumps the efficiency is described by the COP (Coefficient Of Performance), which expresses the amount of useful heat output per work input e.g. produced kW heat per delivered kW electricity. For comparison, the COP of an electrical resistance heater is 1.0 as it delivers 1.0 kW heat per kW electricity.

The COP is highly affected by the temperature output level. The more the heat pump needs to raise the temperature from the evaporator (the heat source) to the condenser (central heating system), the less efficient it is (lower COP). That is why heat pumps are most applicable when combined with low temperature emitters.

	Underfloor heating 25-45 °C	Low temperature radiators 55-60 °C
ASHP, air at -20 °C	2.2	-
ASHP, air at 0 °C	3.8	2.2
ASHP, year-round	2.7-3.0	2.5-2.7
GSHP, ground at 0 °C	5.0	2.9
GSHP, ground at 10 °C	7.2	3.7
GSHP, year-round	3.4-3.8	3.1-3.5

COP for different heat pump configurations

Solar thermal collectors

Solar energy is a free highly efficient and renewable energy source (RES) that may be utilized for domestic and commercial HVAC applications in so-called low and medium-temperature solar thermal collectors. The only energy consuming part is the pump necessary to transport the collected energy around the system.

The solar thermal collectors are often located on roofs or other exposed areas, where they may extract as much energy from the sunlight as possible. A circulating refrigerant is heated in the collectors and from there stored in a solar storage tank and thus separated from the rest of the heating system. The storage tank is an essential part of a solar thermal system, as it allows all the heat being generated by the solar thermal collector to be stored for use whenever it is needed. The heat is transferred to the distribution system or central heating system by a heat exchanger in the tank. Depending on the system design, temperatures as high as 60-90 °C may normally be achieved. The use of solar thermal energy will reduce the need of fossil fuel based heating; however, it will not be possible to cover the entire heating need throughout the year. The efficiency and necessary capacity is very dependent upon the geographical location and intended application of the system.

Solar thermal panels

Closed loop solar systems

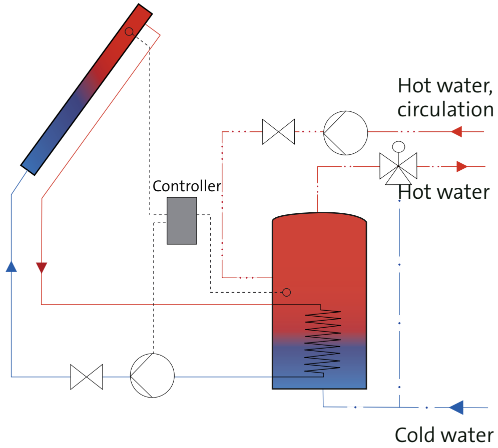
Closed systems are characterized by the pipes, and collector is pressurized and constantly water filled. In order to avoid freezing during low winter temperatures, glycole is added to the water.
Indirect systems include a heat exchanger, which separates the closed collector loop from the potable water.

Solar systems with both domestic hot water heating and space heating

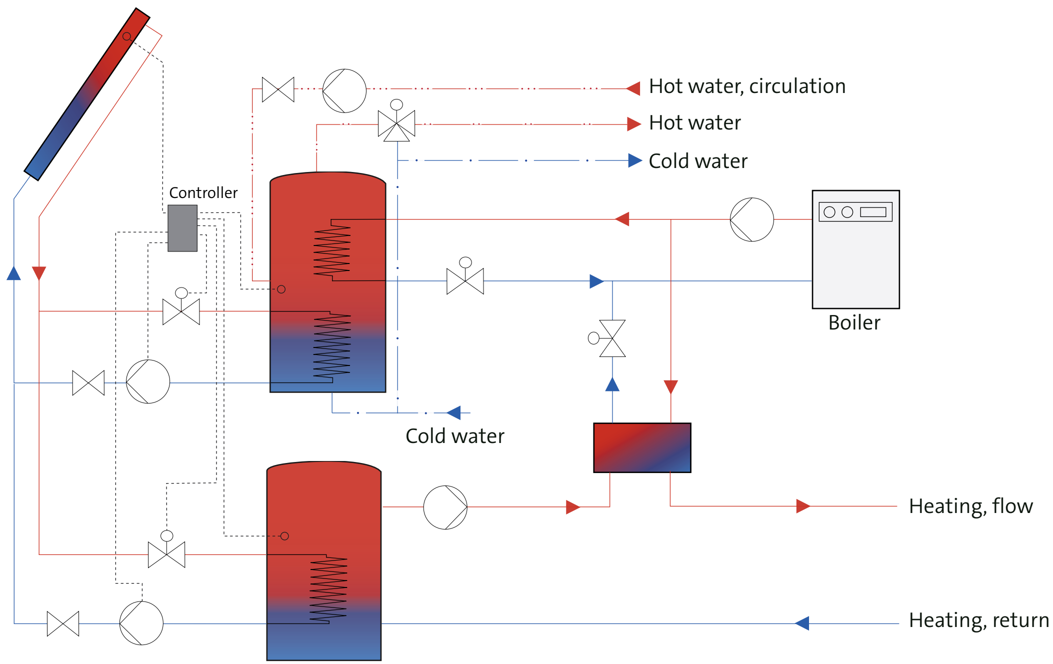
Here the hot water often is prioritized. Only when there is surplus solar heat production, the heating tank is supplied. The stand-by boiler covers peak load situations by supplying both tanks.

District heating

District heating describes a water-based heating system where there is a considerable distance between the place the heat is generated (power plant) and the place the heat is used (the building). District heating is found in the majority of larger cities and big campus areas. District heating is discussed in the separate Grundfos Application Guide for District Heating.



Solar system for domestic hot water heating only.



Solar system with both domestic hot water heating and space heating.

Heat distribution and control

From the heat producing plant or district heating network, water needs to be distributed in the building. To do so, different setups and schemes may be applied depending on the current task.
In order to ensure good system control and operation of the heating system, it is very often divided into primary, secondary and tertiary systems with means of for example mixing loops. Depending on the mixing loop configuration, the flow control or heat mixing may either be done with constant or variable flow and temperature.

Governing equation for heat flow control

The transportation of heat in hydronic systems may be described by the following physical relationship.'

$\Phi = Q \times \rho \times c_p \times (t_f - t_r)$ where

Φ = Heat flow [kW]
Q = Volumetric flow [m^3/s]
ρ = Density of fluid [kg/m^3]
c_p = Specific heat capacity of fluid [kJ/kgK]
t_f = Fluid flow temperature [°C]
t_r = Fluid return temperature [°C]

In this context, the volumetric flow and temperature difference are directly proportional meaning that a given change in fluid flow will affect the overall heat flow in the same way as the change in temperature. On the basis of this connection, the transportation of heat may either be controlled by varying the fluid flow or the temperature of it.
In practice the fluid flow is controlled by throttling valves and the temperature by mixing the supply flow with return flow. These mechanisms are described in the following sections.

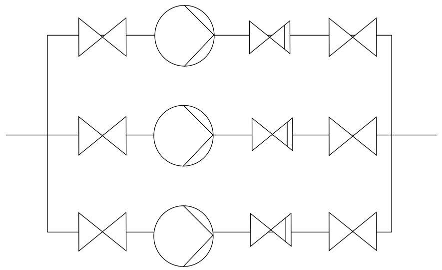
Main pumps

The hot water is distributed around the main system by a set of main pumps. Due to variation in the heat demand and the flow, it is recommended to use speed-controlled pumps in parallel. By speed controlling all the pumps it is possible to obtain an increased energy efficiency which is particularly important at the duty point where the system has a high number of operating hours.

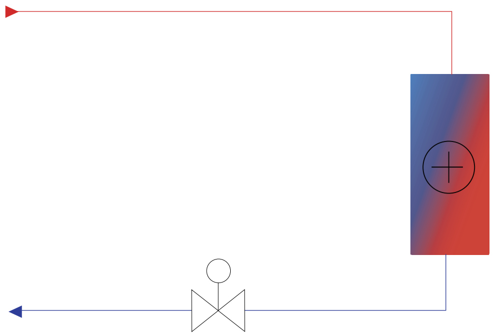
Pipe couplings for constant temperature

In its simplest form, the distribution system directly connects the heat production with the heat emitters without any heat exchange or mixing in the system. In such systems the distribution and control relies on flow variations across the heat emitter as the supply temperature is constant throughout the system. From the two schemes below it is seen how the flow may be controlled by 2-port or 3-port valves, the difference being variable or constant flow in the main pipes. The 3-port valve distribution scheme is used for systems that require a constant water flow.

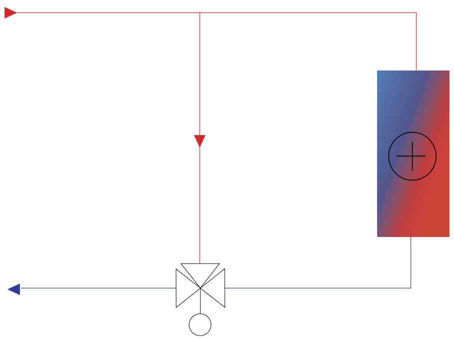
These direct flow controlling systems may be applicable in zone heating coils and radiators. However, as these schemes do not allow temperature control and/or different supply temperatures for different sub-systems of heat emitters e.g. heating coils and radiators, they best serve as final flow control before the heat emission. To ensure the best temperature control, mixing loops need to be incorporated before the final flow control.



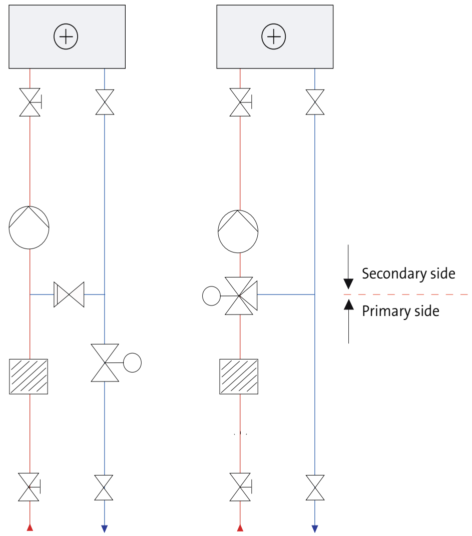
3 main pumps connected in parallel secures flexible and reliable operation.



2-port valve directly adjusts the flow through the consumer and primary circuit.



3-port valve enables reduced flow through consumer without adjustments of flow in primary circuit.



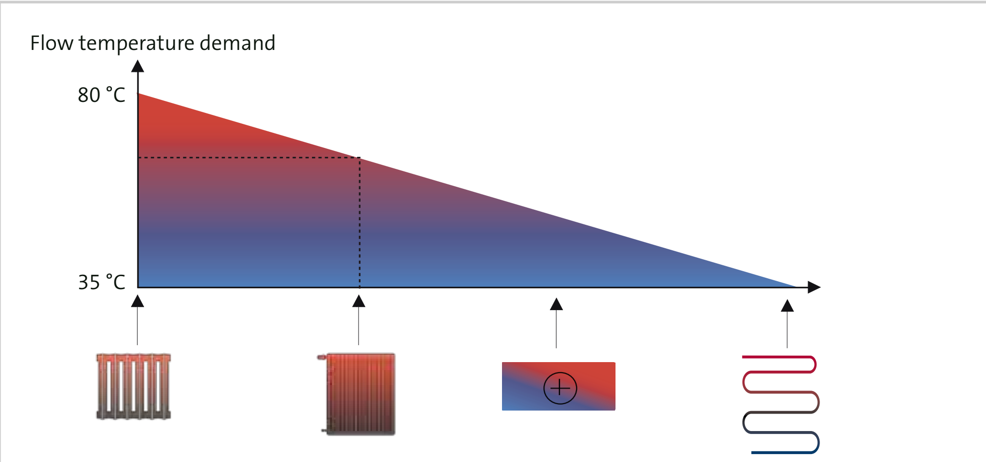
Two ways of constructing a standard single shunt mixing loop. Left: Mixing loop with a 2-port motorised control valve. Right: Mixing loop with a 3-port motorised control valve.

Mixing loops for variable temperature

With different consumers in the central heating system, mixing loops or shunts may be used to ensure the adequate flow and temperature at each zone in a heating system. At least 2-3 and often more sub-systems are needed when having district hot water production, heating coils and room heating in e.g. radiators. Since each system has different requirements, they will normally each require a mixing loop. Such temperature mixing loops are constructed in many different ways. Here standard single shunt mixing loops with 2 and 3 port valves are discussed.

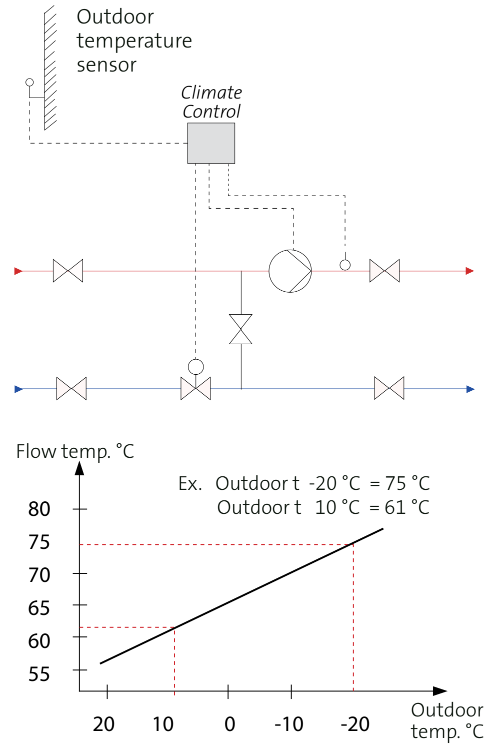
The standard single shunt coupling (see figure) is the most widely used mixing configuration and is used in all areas or heating and cooling applications. It gives a big control accuracy and it enables either a constant or variable flow on the secondary side. Another used variant is the double shunt coupling that enables constant flow in both primary and secondary circuits, which may be beneficial when supplied by e.g. a boiler that requires constant flow. Moreover, it lowers the risk of interference from neighbouring circuits. Apart from that it maintains the same advantages as the single standard shunt configuration.

Heat exchangers may be used for temperature control when wanting to completely separate two circuits. Such systems are also often referred to as indirect due to the separation making the transportation of energy indirect. Heat exchangers are beneficial when having two different fluids as e.g. in heat pumps or hot water production or simply if the owner of a district heating network requires a separation for leakage considerations or to divide the multi tenanted usage. Moreover, it secures a better hydraulic decoupling and also makes it possible to address pressure precautions locally in big systems.

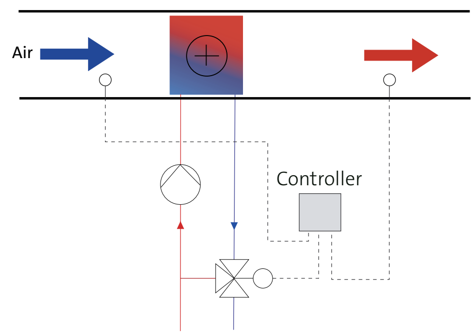


Old cast iron radiators	New light convection radiators	Heat coils (AHU) (Fan coils)	Under floor heating
- High radiation - Low convection	- Medium radiation - Medium convection	- Only convection - Air driven	- Only radiant - Large surface

In a heating system, different types of heating consumers are often installed with different flow temperature requirements.



Example of a special mixing loop application – the so-called climate control with the purpose being to centrally regulate the supply temperature as a function of outdoor temperature.



Example of a mixing loop setup for a heating coil with feedback signal of the controlled air temperature after the coil. By also measuring the inlet air temperature before the coil, the controller may accurately adjust the inlet air set-point based on a pre-programmed climate control.

Mixing loop controls

As the purpose of the mixing loops is to regulate the water temperature, it needs a control system with set-point and a water temperature feedback signal. Such control systems may be configured in many different ways depending on the nature of the application, however, it always consists of a controller (P, PI or PID), which based on input signals regulates the water temperature by either throttling valves and/or adjusting pumps.
In radiator systems both temperature and flow control is normally utilized. The supply temperature is centrally regulated in a mixing loop as a function of outdoor temperature thus minimizing the energy consumption. This regulation is often referred to as "climate control" and relies on a pre-programmed relationship between outdoor air temperature and supply water temperature.

Moreover, the delivered heat on room level is regulated by varying the flow through the radiator by the use of thermostatic valves. Drawing on both temperature control and flow control, these systems enable optimal control and energy efficiency.

In heating coils, mixing loops are used to control the inlet air temperature by mixing the right supply water temperature for the heating coil based on a feedback signal of the current inlet air temperature, which is continuously evaluated up against a set-point, making it a bit different from the weather compensation control.

Overall control system layout

Mixing loops, heat exchangers etc. are examples of decentralized devices or sub-controls that may be used to control the fluid near the end consumer or in the junctions of the heating system. As such these sub-controls are not necessarily required but often very practical in obtaining the desired functionality – all depending on the overall control system layout. Below are examples of how a heating system could be configured.

Primary only system

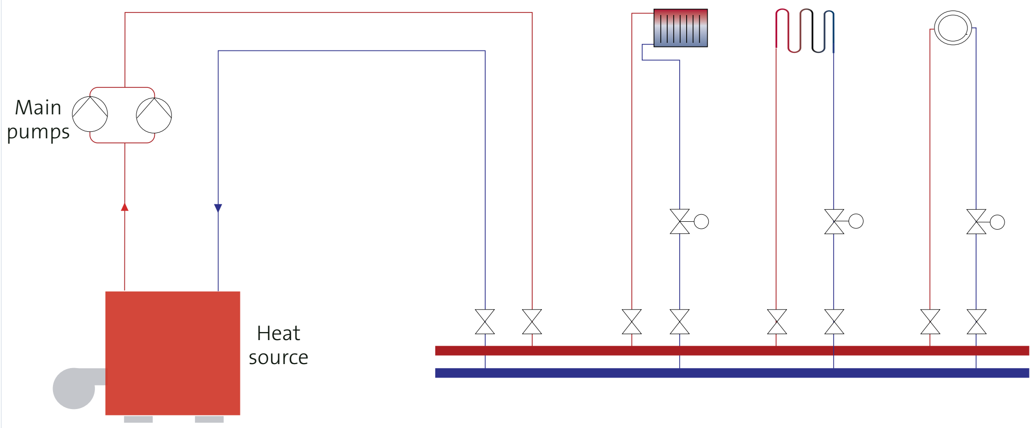
The simplest system construction – a so-called primary only system – relies on direct flow connection from supply to end consumer without any decentralized temperature control. A single set of main pumps pressurises the entire system and thus enables flow control only (same temperature in entire system). Pumps should be variable speed pumps controlled by differential pressure.

Advantages:

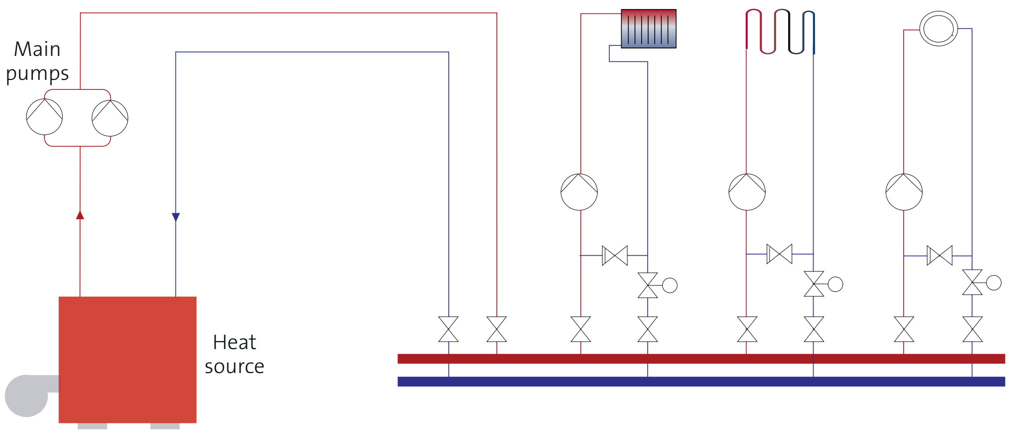
- Simplicity
- Minimal heat loss from heat exchanging devices and additional piping

Disadvantages:

- High differential pressure throughout the system and thus a risk of hunting in low load operation
- Same flow temperature for all consumer types
- Risk of low-efficient boiler operation due to high return temperature



Example of a primary only system with a single set of main pumps pressurizing the entire system.



Example of a primary/secondary system with main pumps in primary circuit and smaller secondary pumps in mixing loops.

Primary/secondary system with main pumps and mixing loops

A more refined variant of the primary system introduces the usage of mixing loops separating the flow in a primary and a secondary side, enabling decentralized temperature and flow control. Main pumps pressurise the primary side only while smaller secondary pumps pressurises the secondary sides. This will help obtain a better hydraulic balance in the total system. Secondary pumps may be ON/OFF controlled or controlled by differential pressure resulting in variable flow in the primary circuit depending on the need. Speed-controlling the primary pumps makes it possible to obtain significant energy savings.

When using 2-port control valves in the mixing loops the pressure lost in the valve is managed by the primary pumps.

Advantages:

- Small differential pressure throughout system
- Possibility of different supply temperature at consumers
- Possibility of both constant and variable flow in secondary circuit

Disadvantages:

- Larger energy consumption for pump operation than a primary/secondary system without main pumps in primary circuit
- More complex and expensive construction than the primary only system

Primary/secondary system with mixing loops with 3-port valves

Here the mixing loop pumps pressurise the entire system, and therefore primary pumps are not necessary. In this system mixing loop valves should be of 3-port type.
This system should only be used if variable flow is accepted in the primary circuit and pumps should be controlled by differential pressure.

Advantages:

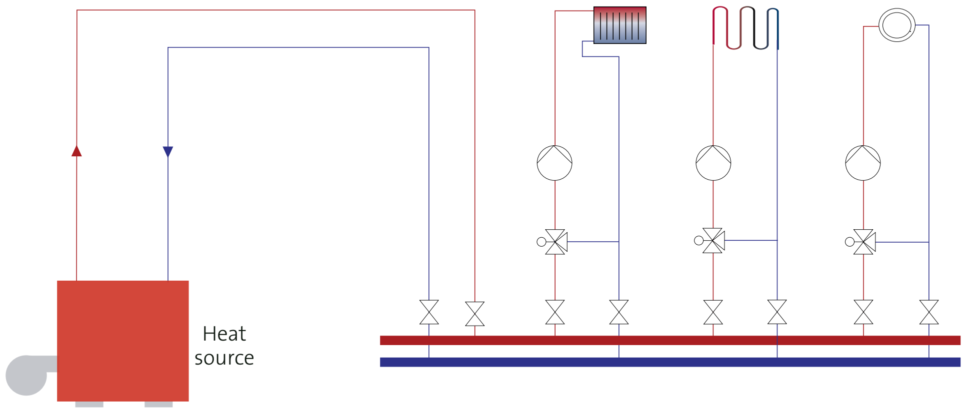
- Minimal energy consumption for pump operation
- Possibility of different supply temperature at consumers
- Possibility of both constant and variable flow in secondary circuit

Disadvantages:

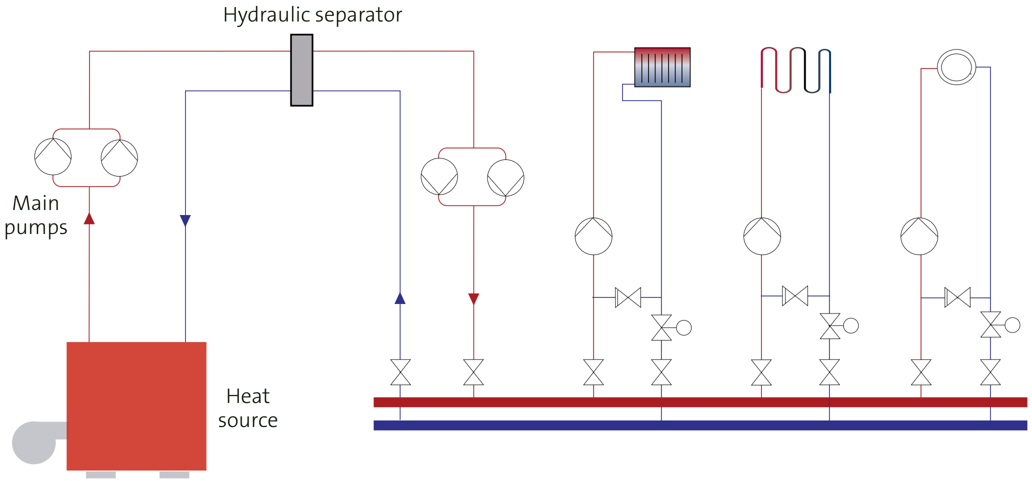
- Only variable flow in primary circuit
- Larger differential pressure throughout the system than in a primary/secondary system with main pumps in primary circuit
- More complex and expensive construction than the primary only system

Primary/secondary/tertiary system with hydraulic separator and mixing loops

The primary side comprises the separated boiler circuit and requires its own pumps. The distribution circuit, the secondary side, supplies the mixing loops, making them the tertiary circuit in the system. As with the primary/secondary systems described above, the secondary/tertiary side may be configured without main pumps where mixing loop pumps only take≤care of pressurisation. In this case, the central valves must be of 3-port type.



Example of a primary/secondary system with secondary pumps in mixing loops pressurizing the entire system.



Example of a primary/secondary/tertiary system with hydraulic separation between primary and secondary circuits.

Advantages:

- Hydraulic separators are traditionally used in heating systems with boilers with a limited water volume and in systems with boilers with a poor turn down ratio. Such systems will have a high cycling ratio which leads to boiler inefficiency. In order to reduce boiler cycling ratio and reduce the risk of sudden water boiling due to very rapid water heating, a hydraulic separator is inserted in the system. As a larger water volume and flow is at disposal, boiler cycling is reduced as well as the risk of local boilling at the boilers heat surface.

Disadvantages:

- Flow commissioning should be carried out very carefully, because primary and secondary flow should always be equal
- If primary flow is greater than secondary flow, mixing will occur in the hydraulic separator. A portion of the primary flow will move downwards in the hydraulic separator and will mix with the cooled return water from the secondary side. In this case the primary return temperature will increase. If a condensing boiler is used, the boilers efficiency is compromised because flue gas condensation may not be achieved
- If secondary flow is greater than primary flow, mixing will occur in the separator. In this case a portion of the cooled returning water from the system will move upwards and mix with the hot water coming from the building. This will reduce the secondary flow temperature and compromise the systems heating performance

Pipe configurations

Basically, there are three categories of pipe systems: one-pipe systems, two-pipe systems and the two pipe system with reversed return.

One-string heating system

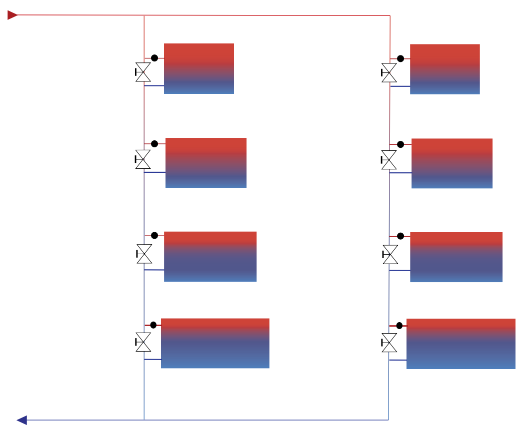
The one-pipe system is rarely used because heating consumers (radiators and heating coils etc.) farthest away from the heating producer have to be sized for a decreasing temperature. This means that the size of the heating surfaces in a building have to increase as the flow temperature decreases. One-string systems are primarily installed in residential buildings.

Advantages:

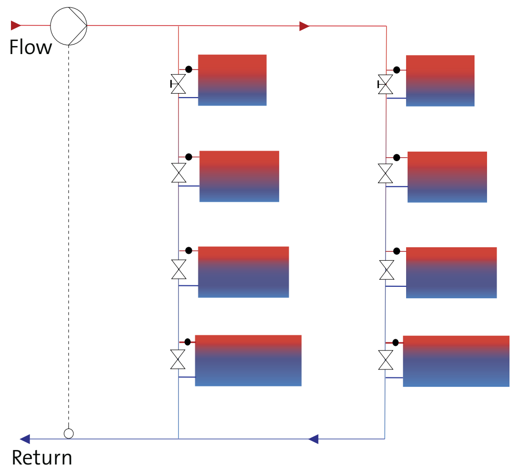
- Only few pipes are necessary
- Possibility for very high cooling of the heating water, which is important when working with condensing boilers and district heating

Disadvantages:

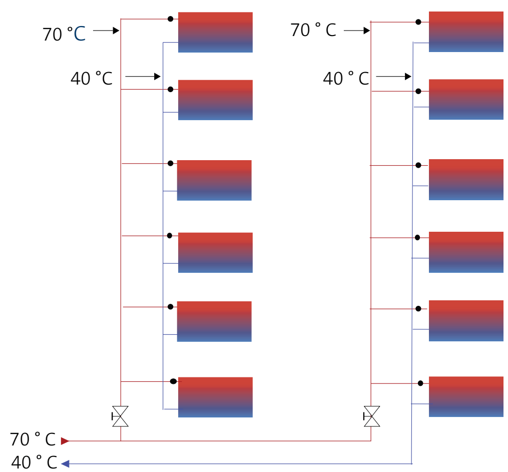
- Risk of high return temperatures at low load conditions
- Complicated design as the heating surfaces varies greatly in size
- Risk of mistakes during installing heating surfaces
- Advanced water balancing of every heating surface
- Heating surfaces are space consuming at low temperature ends
- Extension of a one-string system will create a hydronic unbalance



Example of a one-string heating system. Here the radiators are operating with decreasing flow and return temperatures.



An example of a variable flow pump running in deltaT control mode by input from pump-integrated temperature sensor and an external sensor. If the deltaT in the system becomes too low, the pump will ramp down its performance and vice versa.



Example of a two-string heating system. Here all radiators are operating under the same temperature conditions.

ΔT control of one-string heating systems

Modern smart pumping technology makes it possible to obtain the most efficient control and operation of the one-string system by implementing temperature-controlled smart pumps, which continuously adjust the water flow in the system to the current load situation securing the desired return temperature and maximum system efficiency at all times. In order to sustain high temperature difference in the system, the pump will react to a reduced temperature difference by ramping down its performance and vice versa. ΔT control is well suited in systems with condensing boilers and systems connected to district heating networks.

Two-string heating system

A general characteristic of a two-pipe system is that the radiators are dimensioned for the same flow temperature and the same temperature difference. In a two-pipe system with direct return system, the pressure loss is significantly lower at the closest radiator than at the most distant radiator. In order to avoid increased water flow the system has to be balanced. The system is divided into sections or zones, which are balanced separately. Furthermore, the heating surfaces are supplied with thermostats, which are pre-adjustable for balancing.

Advantages:

- Simple and well known system
- Piping is straight forward, which makes system extensions easy
- Every heating surface has the same temperature conditions which makes sizing easy
- All heating surfaces are the same size, reducing the risk of building site mistakes
- Well suited for condensing boilers and district heating

Disadvantages:

- Individual pre-setting of thermostats is needed
- Need for pipe sections (zone) balancing

Two-string heating system with reversed return (Tichelmann system)

A two-string system where each radiator in the same section has the same total distribution pipe length (supply + return measured from the pump through the radiator and back to the pump) is called a Tichelmann system. It is also referred to as a reversed return system.

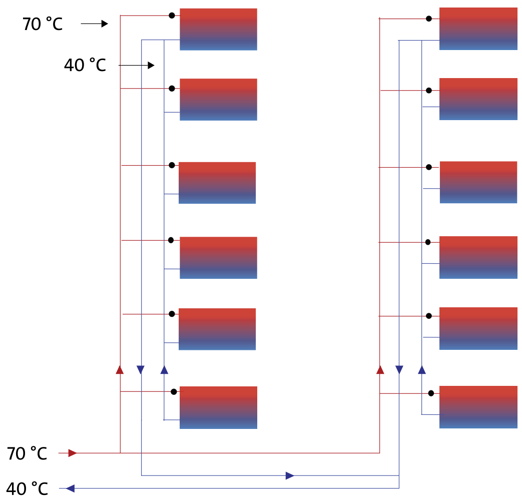
Radiators with a short length of supply pipe measured from the pump have a correspondingly longer return pipe. The opposite applies to a radiator located furthest away. This ensures uniform resistance and hence more or less equal water flow-rate in the heating surfaces. Consequently, the water flow for each heating consumer does not need to be individually adjusted during commissioning.

Advantages:

- Uniform pressure loss to all heating surfaces
- No need of individual pre-setting of thermostats
- Every heating surface has the same temperature conditions making sizing easy
- All heating surfaces are the same size reducing the risk of building site mistakes
- Well suited for condensing boilers and district heating

Disadvantages:

- Longer and more complicated pipe runs
- Slightly higher pumping costs



Example of a two-string heating system with reversed return. The reversed return system is named after Albert Tichelmann, an engineer within the field of hot water.

Good indoor climate is crucial to any commercial building

System balancing

Hydronic heating systems can satisfy even the most demanding requirements for indoor climate if it is well designed and properly balanced. In practice, common problems include:

- Energy costs are higher than expected
- Installed power is not deliverable at the consumers
- Temperatures are varying
- Too hot in some parts of the building, too cold in other parts
- Slow control and regulation
- Long delay before the desired room temperatures are achieved in the morning

These problems often occur because the mechanical design of the heating plant does not meet some conditions necessary for stable and accurate control.

Three important conditions that have to be met in order to ensure a well-balanced system:

- Design flow should be available at all consumers at all times
- The differential pressures at control valves should be stable
- Water flows at system interfaces should be equal

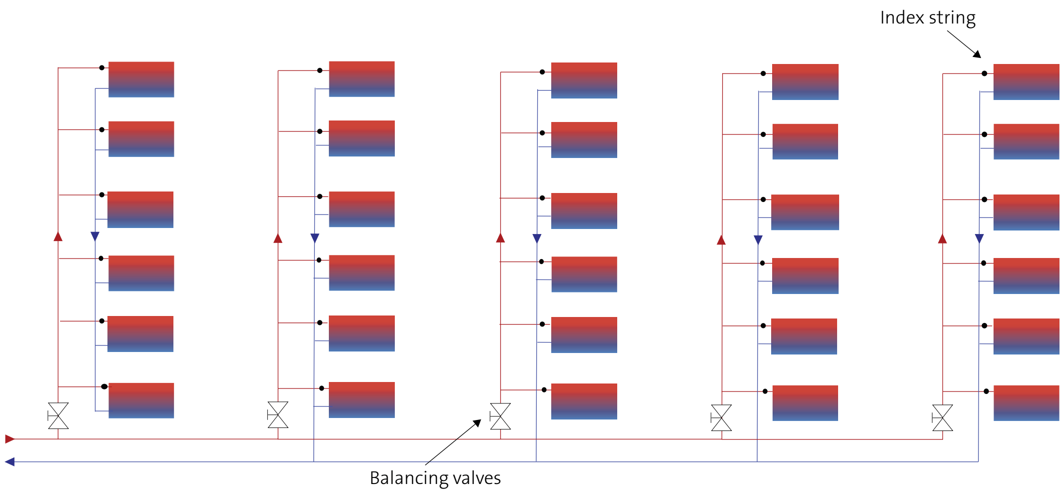
Design flow should be available at all consumers at all times

The heat output by a consumer unit depends on the supply water temperature and the water flow. If the temperature is controlled at the heat production unit or by mixing loops the water flow, at every consumer, is the determining factor for the heat output. In situations where the system is running at design load, a lack of flow will result in insufficient room temperatures and poor indoor climate. In fact, control is only possible when the required water flows are available.

In order to minimize the risk of too low flow, both heat production units, the distribution system and consumer units are often oversized by adding a security factor. However, even if some problems are solved that way, others are created, particularly on the control side. Some oversizing cannot be avoided, because pipes and components must be selected from existing commercial ranges. These generally do not fit the calculations made. In fact, the only component that can be adapted to the actual and correct water flow and pressure is a variable speed pump.

Balancing a heating system means that all surplus pressure in the distribution section strings are removed except pressure in the string with the highest pressure loss (index string). This secures an equal water distribution in the different parts of the heating system but requires balancing valves on all strings.

Balancing should be done under design conditions in order to safeguard that too low flow never occurs at any consumer unit. When every consumer unit in the system is supplied with the design flow, the pressure loss in the system is at its highest. When the load and hence the flow are decreasing, the pressure loss in pipes and components decreases exponentially and the differential pressure at the components will increase. If the flow is sufficient at design conditions, there will always be sufficient flow at all other conditions too.

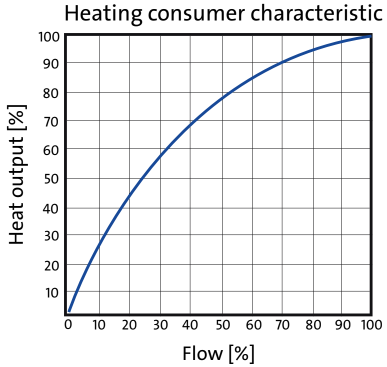


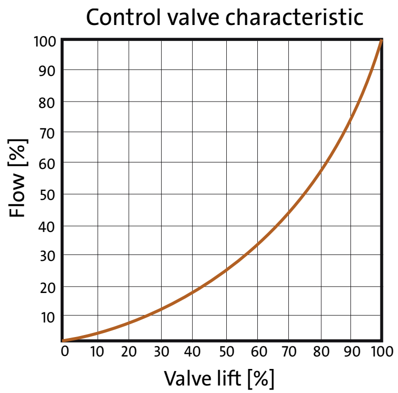
Example of a well-balanced system. All radiators are supplied with sufficient and equal flow due to balancing valves on all strings. Radiators should always be fitted with thermostatic valves with flow pre-setting.

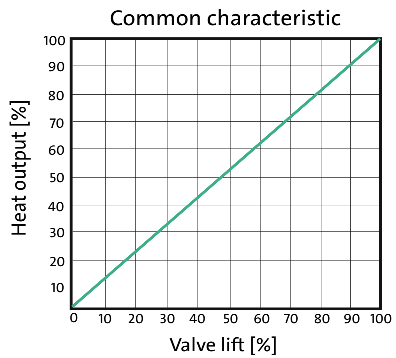
The differential pressures at control valves should be stable

The task of the control valves is to control the heat output of the consumer units e.g. radiators and air heating coils in accordance with the signal from the BMS system or other control unit. This is no easy task because most heating consuming units have a non-linear characteristic. This means that even a small opening of the control valve can increase the heating output disproportionately. Choosing a control valve characteristic to compensate for the non-linearity of the consumer unit may solve this problem. This ensures that the output from the consumer unit is more or less proportional to the valve lift. In this case the pressure difference must be constant, otherwise the valve authority β is reduced and the characteristic of the control valve is distorted.

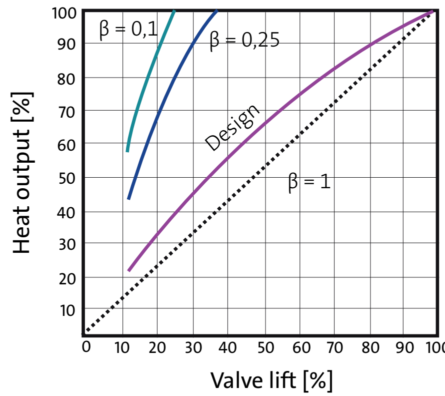
In systems with variable flow the differential pressure at the control valve varies according to the flow. When the flow is reduced the pressure loss in pipes and components decreases exponentially and the differential pressure across the control valve will increase. An increase in the differential pressure distorts the control valve characteristic and hence the combined characteristic. The consequence of this is a decrease of the control valve authority, β, which represent the distortion. The valve authority, β, should always be at least 0.5. The lower valve authority, the higher the distortion. A balancing valve installed in series with the chosen control valve does not change any of these factors and consequently does not affect the control valve authority.



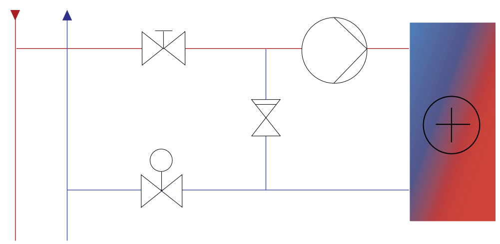




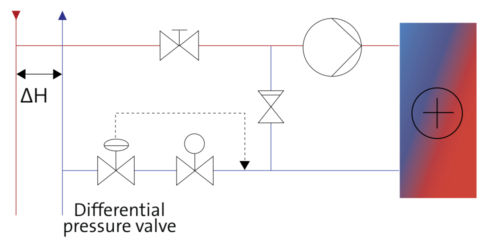
Successful combination of non-linear control characteristics of a heating consumer and a control valve.



Loss of valve authority reduces the valves ability to operate properly and the result might be hysteresis, which might result in undesired room temperature variations.



Balancing valve in primary circuit in a mixing loop.



A differential pressure valve increases the valve authority of the control valve to 1.0.

$$\beta = \frac{\Delta p_v}{\Delta p_a} \quad \text{where}$$

β = Valve authority [-]

Δp_v = Pressure drop in the control valve fully open at design flow [Pa]

Δp_a = Available pressure difference at the closed control valve [Pa]

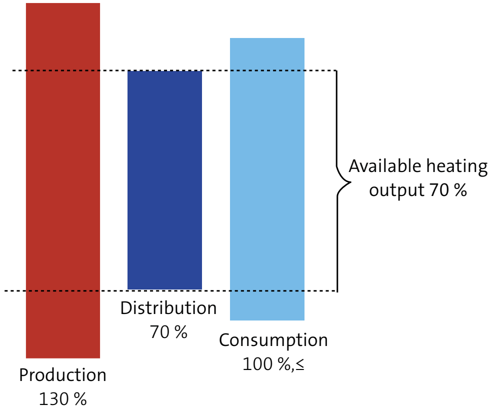
Control valve sizes increase with 60 % in each size. Kvs = 1.6 – 2.5 – 4.0 – 6.3 – 10 – 16 – 25 – 40 etc. This often makes sizing difficult and the result is too high flows in the strings. Balancing the system with a balancing valve secures that the flow in the design load situation is correct.

When the circuit is subjected to major changes in ΔH, a differential pressure controller can stabilize the differential pressure across the control valve ensuring optimal controllability by raising the valve authority to 1.0. When the differential pressure increases, the valve closes proportionally and keeps the differential pressure on the control valve almost constant.

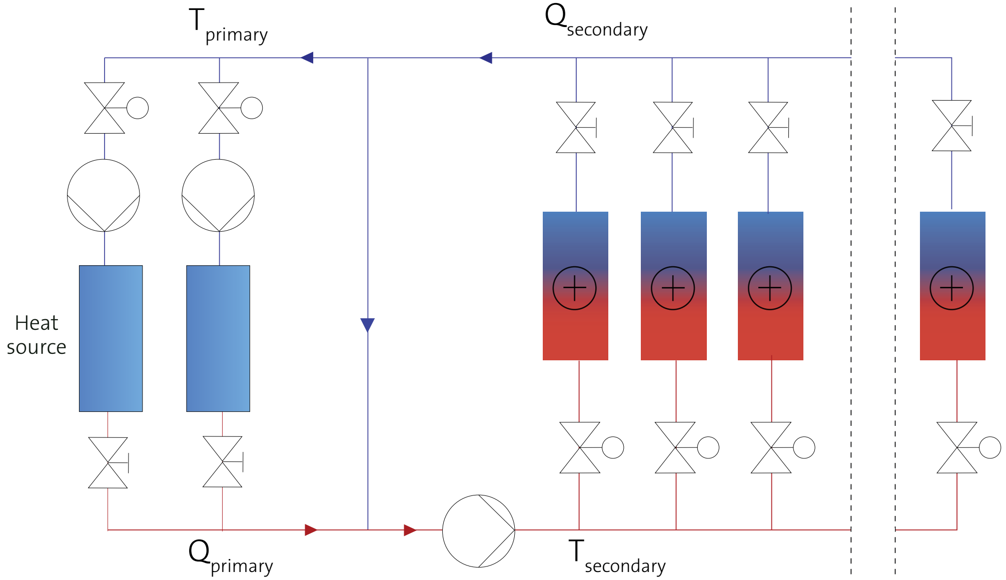
Water flows at system interfaces should be compatible

In many heating systems the available heating production exceeds the need with 25 % or more even if a diversity factor has been taken into account. Nonetheless, the heating consumer units do not always receive the desired heating. If the maximum load cannot be reached, it is often because the plant is hydraulically unbalanced. When peak demands occur, control will open at 100 %. If they are oversized, a too high flow in some parts of the heating system creates underflows in other parts. These unfavoured circuits are not able to provide their full load when required. Furthermore, the production flow will exceed the distribution system flow. In this case the flows are incompatible and the desired flow temperature cannot be reached.

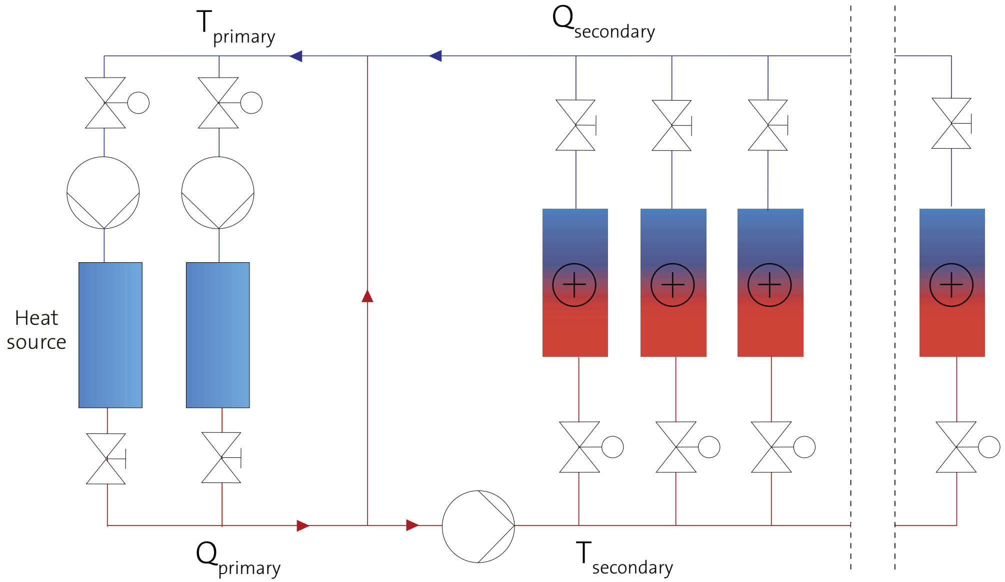
The figure below represents a heating system with two boilers and a number of consumer units. If the distribution circuit is not balanced, the maximum flow, $Q_{secondary}$, may be higher than the production flow, $Q_{primary}$. In this case the flow in the bypass reverses. The flow water temperature will decrease and the designed heating output cannot be transmitted.



If the capacity of production, distribution or consumption is undersized, the total performance of the system will not meet its design heating output.



An example of a primary/secondary system where the secondary flow is higher than the primary flow.



An example of a primary/secondary system where the primary flow is higher than the secondary flow. The primary flow should always be equal to the secondary flow..

Heating consumers

Transmission of heat energy is basically achieved by convection and/or radiation and only marginally by conduction. The way the heat is emitted results in different perceptions of the thermal environment e.g. high temperature gradients in the air or draught.

Heating coils

When using air as the distributor of heat it is exchanged from water to the inlet air in the heating coils, which normally is an integrated part of an AHU. The heating coil is used to heat fresh air before being injected into the building. The final distribution inside the room is based on convective flows starting from the inlet diffuser. This secures a fast and sensible heating. Often the supply air temperature is isothermal, meaning that it has the same temperature as the room temperature. When doing so, the air cannot be used for heating and should be supplemented by additional heat emitters.
If air is used as the sole distributor of heat without any additional systems, the supply temperature needs to be higher than the room air temperature depending upon the ventilation rate – typically 8-10 °C. This complicates the situation and might decrease the thermal comfort and increase noise level. In high rooms it is difficult to ensure that the hot inlet air reaches the occupied zone, as it will rise towards the ceiling due to buoyancy. This will require high momentum diffusers that are able to deliver the air at high velocities, potentially creating discomfort due to hot air streams. Injection of air at too low temperature creates poor indoor climate due to draught, "cold spots", etc.

Water-based heating coil for integration in an air handling unit. There are different types of heating coils e.g. steam-based heating surfaces and electrical heated coils.

To calculate the needed capacity of the heating coil the following formula is used:

$$\Phi = q_v \times \rho \times c_p \times (t_f - t_r)$$ where

Φ	=	Heat demand [kW]
q_v	=	Airflow [m^3/s]
ρ	=	Air density [kg/m^3]
c_p	=	Air specific heat capacity [kJ/kgK]
t_f	=	Air flow temperature [°C]
t_r	=	Air return temperature [°C]

In order to size pipes and calculate pressure losses in the hydronic system, the water volume flow rate Q is necessary. The following formula is used for determining the resulting water flow in the heating coil:

$$Q = \frac{\Phi \times 3600}{\rho \times c_p \times (t_f - t_r)}$$ where

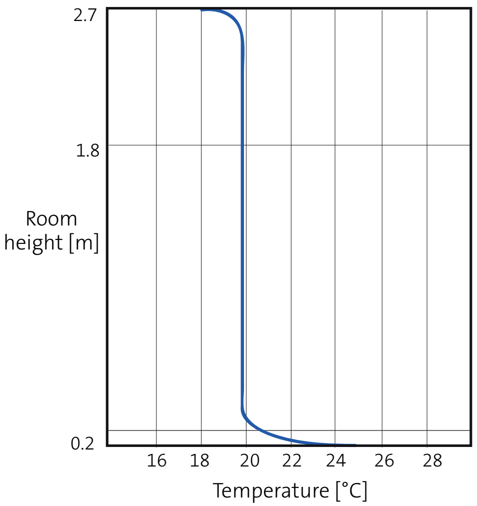
Q	=	Water flow [m^3/s]
Φ	=	Heat demand [kW]
ρ	=	Water density [kg/m^3]
c_p	=	Water specific heat capacity [kJ/kgK]
t_f	=	Water flow temperature [°C]
t_r	=	Water return temperature [°C]

Floor heating

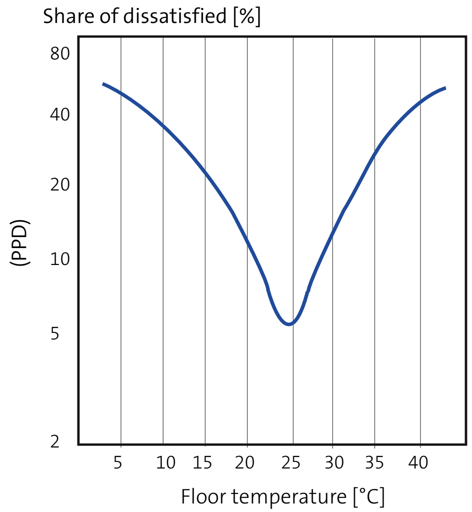
A viable alternative to conventional radiator style heating systems is underfloor heating, which primarily utilizes heat emission by radiation. A typical solution consists of small bore pipes, laid in the concrete slab under the floor surface. The solution is typically fed by a condensing boiler, GSHP or district heating.
Heating buildings in this way provides a consistent, even heat release from floor level. It provides comfort underfoot and pleasant temperatures. Compared to radiator systems it uses a lower water temperature to maintain the same room temperature level.
For the sake of comfort, the floor surface temperature should ideally be between 25-32 °C. This results in a relatively low flow temperature. The obtainable temperature difference will therefore be between 10-15 °C, which is lower than with radiator systems.
Because condensing boilers work more efficiently at lower temperatures, pairing an underfloor heating system can reduce heating costs. A condensing boiler run in the more cost-efficient condensing mode at low temperatures. Underfloor heating is also well-suited for usage with solar heating and heat pumps.

Floor heating systems are characterized by a resulting low vertical air temperature gradient. From just above the floor the temperature stabilizes on a given temperature within the comfort zone, which is defined from 0.2 m to 1.8 m above the floor. If the temperature around the person's head is high and the temperature around the feet is low, this may result in discomfort and dissatisfaction.
The heat is emitted to the room as approximately 60 % radiation, 20 % convection, and 20 % conduction. Each room has one or more circuits, which are commonly controlled by a room thermostat.

Installation of floor heating pipes. The mat keeps the pipes in place before casting.



Typical air temperature gradient in rooms with under-floor heating.



Predicted percentage dissatisfied as function of floor temperature

Capacity of a floor heating system:

$\Phi = \alpha \times A \times (t_s - t_a)$ where

Φ	=	Heat flow [kW]
α	=	Floor surface heat transmission coefficient [W/m²K]
A	=	Floor area [m²]
t_s	=	Floor surface temperature [°C]
t_a	=	Room air temperature [°C]

The floor surface heat transmission coefficient is set between 9.5 and 10.2 depending on the flooring type.

The recommended maximum floor temperature depends on the usage	
Workshops, industrial kitchens	25 °C
Offices, lounges and residential areas	28 °C
Lobbys, foyers	30 °C
Swimming stadions, locker rooms	32 °C

The graph shows the relation between the floor temperature and the percentage of dissatisfied because of thermal discomfort and thus why the floor temperature is of vital importance. In environments where people are sitting or working, the floor surface temperature has to be kept very stable. Nevertheless it is never possible to obtain 100 % satisfied people; a minimum of 5 % will feel in thermal discomfort due to floor temperature.

However in locker rooms and similar rooms where people are bare footed, high floor temperatures are accepted because people are staying there only for a short while.

Water flow in a floor heating system:

$$Q = \frac{\Phi \times 3600}{\rho \times c_p \times (t_f - t_r)} \quad \text{where}$$

Q	=	Water flow [m³/s]
Φ	=	Heat demand [kW]
ρ	=	Water density [kg/m³]
c_p	=	Water specific heat capacity [kJ/kgK]
t_f	=	Water flow temperature [°C]
t_r	=	Water return temperature [°C]

The example on page 17 shows the appliance of the above mentioned formulas in calculating the water flow temperature and flowrate of an underfloor heating system.

Fan coils

In contrary to the heating coil, a fan coil is an independent and unducted heating coil with integrated air fans. As the fan coil is unducted, it recirculates and heats up air within the space where it is located and thus it does not supply fresh air.
A fan coil for heating should primarily be used in storages, car parks, halls and hangars etc. where vast spaces have to be heated and where good indoor climate is of minor importance.

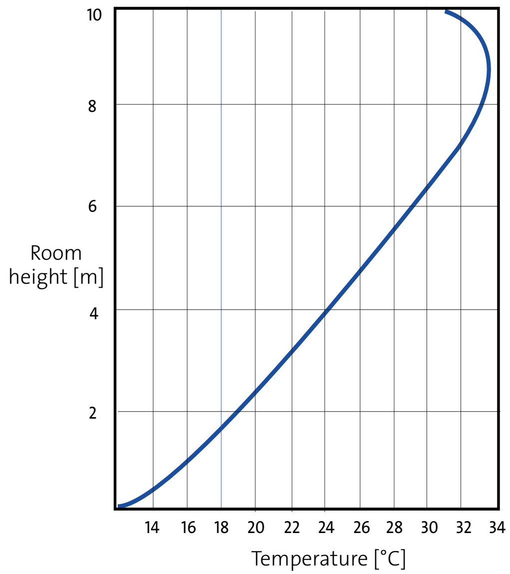
Advantages:

- Low investment cost
- Takes up no floor space

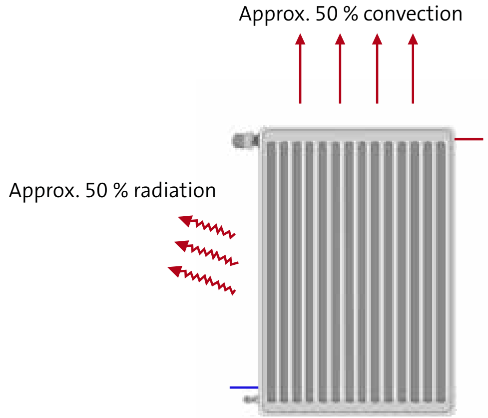
Disadvantages:

- Risk of draught due to large air velocities
- High vertical temperature gradient
- Fans are noisy
- High running cost in relation to hydronic heating (radiators, floor heating)
- Poor heating efficiency in high rooms

Fan coil unit



Typical air temperature gradient in rooms with fan coil heating.



Schematic illustration of heat emission from radiators

Capacity of a fan coil:

$$\Phi = q_v \times \rho \times c_p \times (t_u - t_i) \quad \text{where}$$

Φ	=	Heat demand [kW]
q_v	=	Airflow [m³/s]
ρ	=	Air density [kg/m³]
c_p	=	Air specific heat capacity [kJ/kgK]
t_u	=	Air leaving temperature [°C]
t_i	=	Air entering temperature [°C]

Spaces with fan coil heating systems are characterized with very high vertical air temperature differences. As such fan coils are not suited for heating e.g. office spaces where a comfortable thermal indoor climate is needed. However, fan coils for cooling is very common in all environments. Here the cold air drops down into the comfort zone by itself and an acceptable vertical temperature difference is achieved.

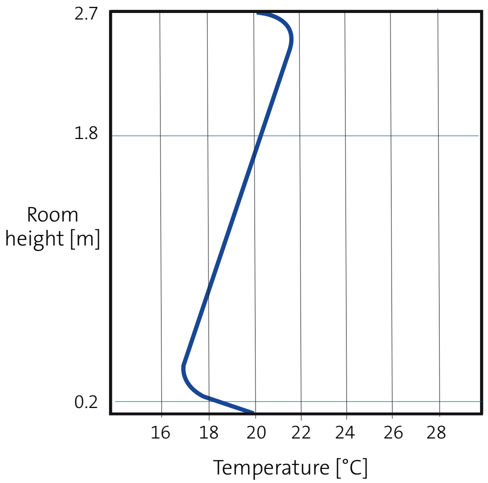
Radiators and convectors

A radiator is a heating surface that transfers the heat by a combination of thermal radiation and convection. The heat transfer from a radiator is typically distributed equally between thermal radiation and convection, though this can vary depending on the design of the radiator.
The utilization of radiation is beneficial in several aspects. First of all, it secures a more even thermal sensation when the surfaces are heated as well. Secondly, a radiant based emitter system can obtain the same operative temperature at a lower air temperature. In industrial buildings with high ventilation rates like warehouses and hangars, even a small reduction in air temperature may reduce the ventilation loss and thus the energy consumption for heating drastically.

Radiators can be fitted with convection panels behind or between the thermal-radiating panels, allowing them to transfer a larger amount of heat via convection. Thus, the total heating capacity is increased.
Using radiators is a good solution in many buildings securing fast, cheap and versatile heating. The separation of heating and ventilation when using hydronic systems like radiators makes it possible to turn off the ventilation when IAQ is of no importance, potentially reducing the energy consumption. This is applicable when wanting to pre-heat the room before people entering it or when having a natural driven ventilation strategy.
A given radiator's heating capacity is dependent on the temperature difference between the medium flowing through the radiator and the air temperature of the room. A radiator's nominal heating capacity is specified for a set of standard conditions in terms of supply, return and room temperatures. The actual heat output of a given radiator for a given set of non-standard conditions can be calculated with the use of conversion tables or radiator exponents.

Hydronic heating systems with radiators are characterized with medium vertical air temperature gradients. From just above the floor the temperature stabilizes on a given temperature. Within the comfort zone, which is defined from 0.2 m to 1.8 m above the floor, this is very important.

Radiators come in many different shapes and sizes



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