Chapter 2
Radiators in Hydronic Heating Installations. Historical Outline, Types and Structure

2.1 Historical Outline

The idea of heating the place of human habitation is as old as mankind. As it evolved, a gradual transformation occurred in human lifestyle—from wandering to hunt and collect food into farming and breeding animals. As a result, people started to spend more time in one place. This contributed to the rise of communities and created a need to build solid shelters that were no longer abandoned if food had to be looked for elsewhere. Settled in one place, people began to search for improvement in their domestic comfort. Heating their homes was one of the first steps to achieve that. The earliest and the most primitive methods that could hardly be called heating systems were open fires with a roof opening that were later replaced with closed fireplaces that could be referred to as *hearths*. Still, they were far from what can be qualified as a heating system, let alone a central heating system.

The idea of a heating installation being an autonomous facility of a residential building has been known for thousands of years. It was already used in ancient times and referred to as *hypocaustum*. Archaeologic findings prove that this installation type appeared as early as about 2000 BC [1]. *Hypocausta* were used on a large scale in ancient Greece (about the 4th century BC) and in ancient Rome (about the 1st century BC). They were used primarily to heat public buildings, such as hot baths, but also private houses. A *hypocaustum* was a system of surface warm air heating. In one of the rooms on the lowest storey, frequently in the basement, there was a furnace heating air which was then distributed through a network of ducts under the concrete/tiles of the room above and, sometimes, also in the room walls.

Examples of such a solution are presented in Fig. 2.1.

A certain variation of this solution was also used in the Malbork Castle. The difference was that apart from heating floors and walls, heat was also accumulated

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Fig. 2.1 A *hypocaustum* central heating system [1]

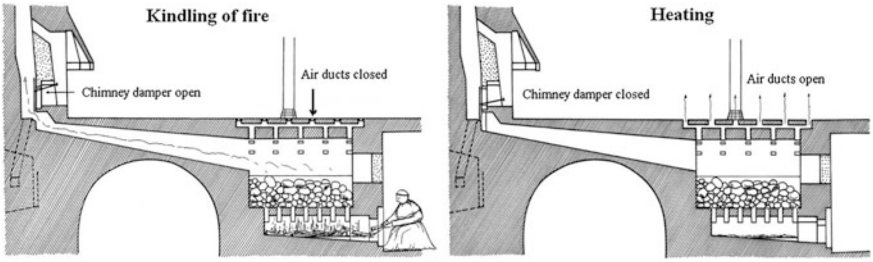

Fig. 2.2 Malbork Castle medieval heating system [2]

in stones placed in an additional accumulation chamber. From there, heated air was introduced into individual rooms through holes in the floor, as presented in Fig. 2.2.

After the fall of ancient civilizations, the heating system technology was not developed much over the next centuries. The solutions mentioned above were used in a practically unchanged form for many epochs with fireplaces being the most popular devices.

A major breakthrough in the room heating technology was made in the 18th century. Attention was then drawn to water as the heat exchange medium between places where heat was generated and given up. Commonly available water, just like air, is a non-flammable and non-toxic substance which became a popular heat carrier and a working medium in turbomachinery (e.g. steam turbines). As a medium, water has a number of advantages over air. Its specific heat is more than four times higher, which means that 4 times more energy may be transported in a given mass unit. Moreover, its density (at atmospheric pressure) is over 800 times bigger. The effect of a combination of the two characteristics is that in a given unit of volume[1] water is able to transport over 3000 times more energy than air.

[1] A volume unit is the parameter to be used because in a given cycle each device pumping a given medium, being a device with specific geometrical dimensions (e.g. the blade height or the piston machine displacement volume), shifts the medium specific volume and not mass.

In addition, the water flow surface film conductance is many times higher compared to the air flow. Owing to that, the applied water flow temperatures and velocities may be much lower than in the case of air.

The idea of the hydronic heating installation was preceded by hot tap water installations. The first such system was put into service in the Summer Palace in St. Petersburg (1710–1714). It was made of a central hot water boiler and a network of richly decorated porcelain pipes delivering water to individual rooms. In the next few years similar systems appeared rapidly in other countries.

Different dates and names of authors of the heating technology solutions can be found in different historical sources. Nonetheless, it is pretty certain that hydronic heating systems were first introduced in greenhouses. In 1716, Swedish engineer Mårten Triewald introduced such a system in a greenhouse in Newcastle. However, for many years such solutions were considered as impractical, and the contemporary specialists in civil and heating engineering did not seem to be interested in the idea. The possible reason for that was that there were no electric pumps at that time and the water flow in the installation was only gravitational. It has to be remembered that gravitational systems are burdened with a number of limitations and they operate correctly only if specific requirements are satisfied.

French engineer Bonnemain, who in 1777 presented a hot water device intended for heating incubators to the French Academy, is considered to be the inventor of the open hydronic heating system. In 1819 marquis De Chabannes published a work on the application of a hydronic heating installation in London flats. According to Feldhouse, the first hydronic heating system in a residential building was constructed in St. Petersburg in 1812 [3, 4].

Solutions based on steam acting as the working medium also appeared around that time. In 1832 in England, American engineer Angier March Perkins launched the first steam heating installation which he designed and patented. The system became extremely popular and was used mainly in English factories and churches. The advantage of a gravitational steam installation over a hydronic (or more commonly—water) heating system lies in the fact that the flow is induced by pressure prevailing in the boiler during the evaporation process. The disadvantages include for example the high temperatures of operation, the high failure rate and the hazards presented to humans (in those years) as well as the need to use facilities intended for drainage and condensate discharge. The development of pump systems occurred on a larger scale in the 1870s, when first electric pumps suitable for use in heating installations started to be supplied by industry.

In 1855 Franz San Galli, a scientist and businessman born in Stettin (Prussian Pomerania, now Szczecin) and living in St. Petersburg, invented and patented a device which was an early version of the now popular radiator. It was suitable for operation in a steam heating installation. Originally, the inventor named it the *hot box*, which was sold under the Russian name *batarieja*, a term still used in Russia as a synonym of the radiator. With some modifications, the device has survived until today. In the second half of the 20th century it was still the most popular radiator type—a cast iron column radiator.

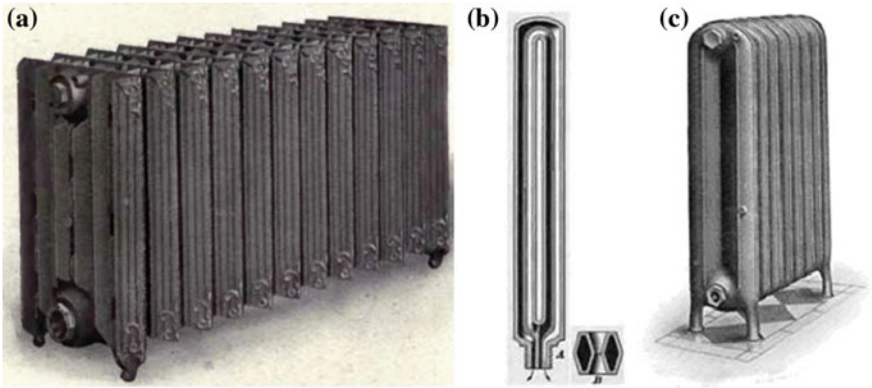

Fig. 2.3 **a** *American Radiators Company* column radiator: *Aetna Flue Window air radiator*. **b** *Bundy Loop* radiator. **c** *Beeston Boiler Company column radiator* [5, 6]

In 1862 in the USA, the *Nason, Perkins and Briggs Company* patented the steam radiator. However, the device named *Bundy Loop*, developed by Nelson H. Bundy in 1872, became more popular. The name comes from the device structure—the cast iron casing had ducts arranged in loops. The radiator is presented in Fig. 2.3b.

In the second half and towards the end of the 19th century there appeared a number of enterprises making radiators and other equipment intended for heating installations. The leader of the years was the *American Radiators Company*. At the turn of the 19th and 20th century the company already had offices and outlets in Europe and launched operation of factories there. One of the devices made by the company in 1905 is presented in Fig. 2.3a. One of the well-known European manufacturers of the heating system equipment and elements was *Beeston Boiler Company* in Nottinghamshire, England. Figure 2.3c presents one of the radiators offered by it in the 1932 catalogue.

Decorative radiators were also made in the shape of ornamented horizontal pipes, rings imitating multi-part concrete columns, fancy trusses, etc. Many such objects can be found in churches or historical buildings.

The development of the production technology of radiators and the heating installation devices occurred in parallel with the progress in the theory of control and operation of heating systems. English scientist Charles Hood was the first to take up these issues [3, 4]. The work published by him in 1837 states for example that the water flow velocity in pipes is proportional to the square root of the difference in the water column height, i.e. to differential pressure. Most probably it was him who introduced the frictional resistance of water flowing in pipes into hydraulic calculations. However, the considerations had a purely empirical basis.

The development of theoretical basics of the heating system operation and hydraulic calculation is attributed to German scientist *Herman Rietschel* and his students, e.g. *Tichelmann*, *Recknagel, Wierz*, *Birlo*, *Missenard*, *Weber* and others [3, 4]. They dealt primarily with the water natural (gravitational) circulation systems.

2.2 Current Realizations of the Concept of a Radiator Intended for a Hydronic Heating Installation

A rapid development of the heating technology occurred after the Second World War. Nonetheless, the only radiator type produced at that time was the cast iron segment radiator also referred to as the *column radiator*. Over time, as open gravitational installations started to be displaced by closed pump systems, some favourable features of the massive cast iron column radiator lost significance and were even viewed as the device limitations.

Nowadays radiators are made mainly of steel. Apart from that, radiators made as iron, aluminium or (rather seldom) copper casts may still be found.

The following radiator types may be distinguished:

(a) segment (column) radiators,
(b) panel radiators,
(c) panel-convector radiators,
(d) convector radiators,
(e) canal radiators,
(f) smooth- and finned-tube radiators,
(g) surface radiators.

2.2.1 Segment (Column) Radiators

Segment radiators, also known as *column* or *fin* radiators are still manufactured today. They are most often made of steel or aluminium, but they are also in the form of iron casts. The term *fin radiator* is a colloquial phrase that originated in relation to the structure and shape of early column radiators. The term *segment radiator* is used due to the structure of the device which is composed of a set of individual segments. The segments may be separable and joined to each other by screws, which is most often the case with cast iron radiators. If a need arises, the radiator heat output may be increased or diminished by adding or taking off an appropriate number of segments. In the case of steel column radiators there are solutions using separable segments joined to each other as well as those based on solid welded devices being an inseparable unit. If the latter is the case, the term *column radiator* is more appropriate. This means that a column radiator may or may not be a segment radiator. Apart from that, there are segment radiators for which the name column radiator is unjustified because they look like panel radiators divided into sections with convection ducts as presented in Fig. 2.4c.

Segment radiators, just like other convector radiators discussed below, may be manufactured in different dimensions, shapes and colours and they may even be custom-made to suit individual preferences. Examples of such radiators are presented in Fig. 2.4.

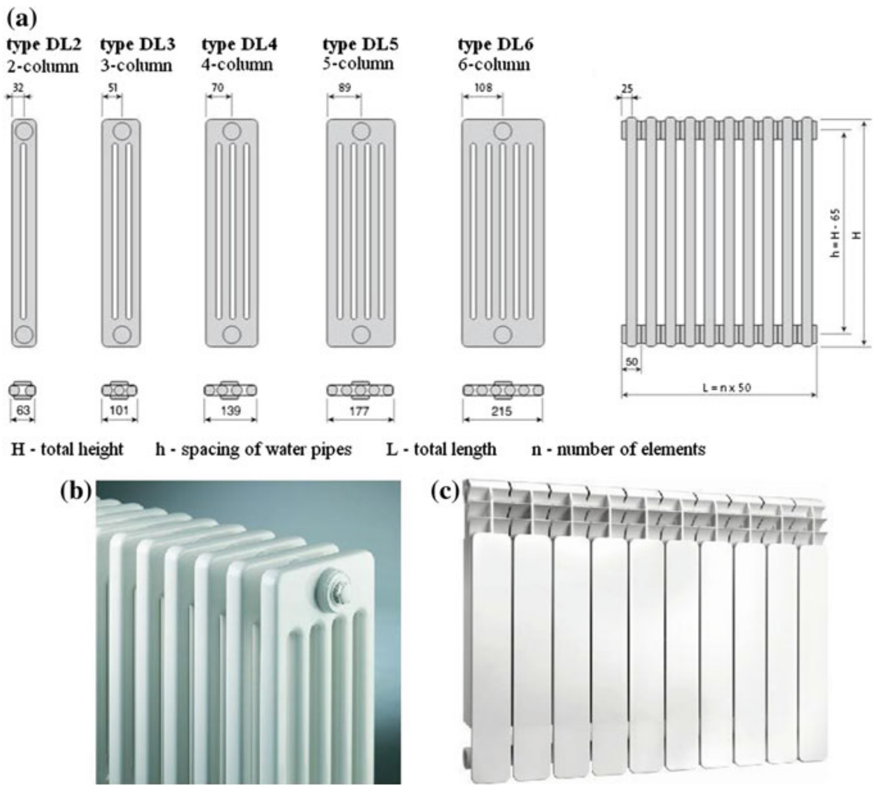

Fig. 2.4 *Purmo Delta Laserline* column radiators **a**, **b**; an aluminium column radiator made by *Armatura Kraków* **c** [7, 8]

The cast iron column radiator has both advantages and disadvantages, a combination of which decides whether or not the device should be used in a given room.

The advantages of this type of radiators are as follows:

– a possibility of changing the radiator size and adjusting its required heat output to the room characteristics,
– high resistance to the effect of water pressure,
– the water flow small hydraulic resistances and pressure losses,
– high resistance to corrosion, including external corrosion, which makes it possible to use the device in buildings characterized by high air humidity.

The disadvantages include:

– heavy weight of the device (in the case of cast iron radiators),
– high water capacity and thermal inertia (in the case of cast iron radiators),
– large unit geometrical dimensions (in respect of a given heat output).

The downsides mentioned above are not very troublesome in the case of an open gravitational system operation. However, in state-of-the-art installations they may impose serious limitations. The radiator large mass and thermal capacity may have been an advantage of a gravitational installation, but in a pump system with automatic temperature control devices needed to ensure thermal comfort and optimize energy consumption these features pose certain problems. High thermal capacity means a long time of the radiator response to changes for example in the supply water temperature or mass flow if thermoregulators or other systems of local or central regulation are used. And this may lead to the room overheating or generation of undue costs if heat gains from people or solar exposure occur.

The advantages of the cast iron column radiator lose their significance in the case of state-of-the-art installations. The resistance to the effect of water pressure is negligible because typical pressure values in home installations are many times smaller than the permissible pressure of any radiator type operation. This feature is desired for example if the building heating system is directly connected to the district heating network, but this solution is unfavourable for many reasons. The resistance to external corrosion is important if the radiator operates in environments with high air humidity, such as bathhouses, swimming pools, laundry rooms, car washes, etc. In a home installation this quality becomes less important and so does the resistance to internal corrosion because modern heating systems are generally designed as closed ones with appropriately prepared water. As a result, the content of dissolved oxygen is relatively low, which minimizes the corrosion phenomenon. The significance of small hydraulic resistances is also slight in pump systems, where active pressure is many times higher compared to gravitational installations, and hydraulic resistances of the other elements and devices are by two or three orders of magnitude bigger than the resistance of the radiator itself.

Aluminium column radiators (or ones made with an addition of aluminium) were created to eliminate some of the disadvantages of cast iron heating devices. They are characterized by a small unit mass and their thermal capacity is relatively low. But they get damaged easily and are affected by electrochemical corrosion. This means that they should not be used in installations containing copper. Otherwise, appropriate chemical agents need to be added to water. Steel column radiators also minimize some weak points of the typical cast iron column radiator. They are lighter and their thermal inertia is smaller.

Aesthetic issues may also be important here. Column radiators have a look that matches classically decorated interiors.

2.2.2 Panel Radiators

The term *panel radiator* is generally used for both panel and panel-convector radiators. They are now the most popular solution commonly used in the building industry. Panel radiators are made of steel by welding together metal sheets and creating small ducts for water to flow through. In this way a single heating panel is made. The radiator power may be raised by fixing fins in the form of corrugated sheets on the panel, which increases the heat exchange surface area and consequently—the radiator heat output. Such a device is referred to as a panel-convector- or a panel-convective radiator.

In the case of multi-panel radiators, water is usually distributed to each of the panels equally. There are also solutions in which water is fed through the panels in series, flowing first into the distribution duct of the front panel, facing the room, and then to the rear one facing the external wall. The temperature of this panel is thus lower, which reduces heat losses. Owing to that, radiation has a greater share in the heat transfer process. On the other hand, connecting panels in series involves higher hydraulic resistances. However, these issues are of slight practical significance and the differences between the number values obtained for the two solutions are small [9]. The difference in the temperature of the panels is not big because the water flowing through the distribution duct of the first one and then feeding the next is not cooled much. The differences would be significant if the second panel was supplied from the first panel collection duct, where the temperature of the water that has covered all the way from the distribution duct through the radiator height is already much lower. The hydraulic resistance, though several times higher than in an in-series connection, does not have any practical impact, either, because the values are still very small compared to hydraulic resistances of the other elements of the pump installation network.

As a construction material, steel offers freedom of the device machining and forming, including precise surface treatment. Panel radiators are most often used in health service centres and hospitals. In some European countries, e.g. in Poland, this is the effect of legal regulations [10] that require that smooth-surface radiators that can be cleaned easily should be used in these institutions. Manufacturers usually call them *hygiene radiators*.

A wide range of variants of the panel radiator may be made with different dimensions and in different colours. The general principle of the panel radiator marking concerns the number of panels and finning, and the radiator height. As a rule, the first digit denotes the number of panels and the second—the number of panels with fins (on one side). The next digit, usually preceded by a dash, specifies the panel height in centimetres. For instance, a radiator with the 22–50 marking has two panels, both with fins (on one internal side), and the panel height is 50 cm.

Panel radiators may also be made in special versions ensuring enhanced resistance to external surface corrosion. This makes it possible to use them in rooms with high air humidity or places where the device may get in direct contact with water.

Panel radiators may also operate in an integrated, natural or mechanical, ventilation system. An attachment connected to a hole in the external wall is fixed to the bottom of the radiator mounted on the wall. The attachment allows an inflow of outside air, which heats up as it passes between the radiator panels. Owing to that, it is possible to directly heat up ventilation air. This increases the radiator heat output compared to standard parameters. The set is usually equipped with air filters and, if necessary, an electric forced-draught fan.

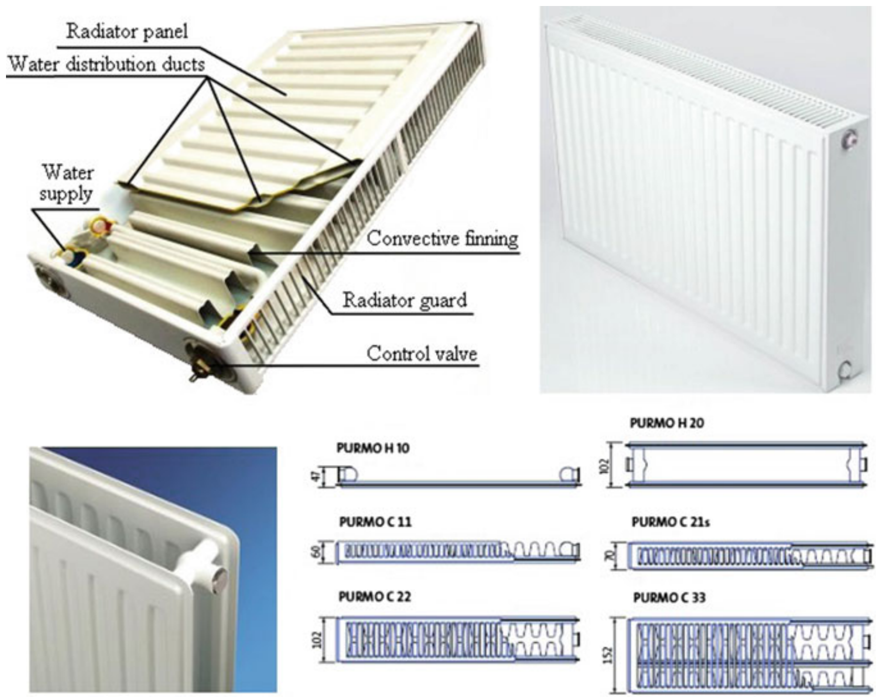

Fig. 2.5 The structure of panel- and convector-panel radiators on the example of selected *Purmo* products [8]

Figure 2.5 presents the structure of panel and panel-convector radiators and the typical markings of the most common models of such devices. A panel radiator with a ventilation attachment is shown in Fig. 2.6.

Panel radiators have many advantages, the most important of which are as follows:

- small unit mass,
- small water capacity (about 3–4 times smaller compared to cast iron column radiators) and small thermal inertia,
- possibility of obtaining any surface finish and shape,
- small unit geometrical dimensions (in respect of a given heat output),
- possibility of achieving a heat output with a high share of thermal power generated due to the radiation heat transfer,
- easy access to heating surfaces and the ease of cleaning (in the case of radiators with no convective finning).

The disadvantages include:

- relatively high hydraulic resistances,
- sensitivity to corrosion.

Fig. 2.6 Panel radiator operating in an integrated ventilation system [8]

The aforementioned advantages of panel- and panel-convector radiators have made them very popular—they are now the most common radiator type in use. Their downsides appear to be significant only in the case of gravitational and open installations, which are currently very seldom. In typical correctly operated[2] systems their importance is slight.

2.2.3 Convector Radiators

A characteristic feature of convector radiators is that their heat output is given up almost entirely through convection, which explains their name. Instead of being distributed in panels, water supplied to the radiator flows through an internal system of usually densely finned tubes. Thermal insulation of panels is also used sometimes. Such a construction prevents heat radiation from these elements of the device. The surface between the panels is very well developed owing to a system of metal sheets and dense finning, much denser compared to panel-convector radiators.

This radiator type may also be equipped with an electric fan to intensify the air flow in the radiator channels to increase the heat output. Such devices are called *fan coils* or *climaconvectors*. In practice, the terms are used interchangeably. However, only a fan climaconvector should formally be referred to as a fan coil because there are structures where the air flow is intensified using the injection phenomenon and not a fan.

Fan climaconvectors are often used in large-sized stores, where they are mounted under the hall roof and connected to the heating and cooling installation.

[2]Correct operation of a heating installation consists, among other things, of using appropriately prepared product water, possibly seldom emptying of the installation (to prevent air from getting into it as this increases the corrosion rate) and filling up losses in the water column with product water.

Their function may thus be heating or cooling. Another typical location where they are mounted is the area close to the entrance door or above it—in the entrance enclosure, where the device blows in warm air creating an air curtain that prevents cold air from getting inside.

The most common solution used in home installations is the standing climaconvector. In this case the fan draws in air from above and discharges it downwards, onto the floor. For a convector, the flow direction is the same as for a typical radiator, i.e. from the bottom to the top. Climaconvectors are most often equipped with electronic controllers to make it possible to set or programme the device operation cycle and regulate the fan revolution number to alter the heating or cooling power.

Convector radiators (i.e. with no fan) may be a favourable alternative to classical panel or column radiators, especially in rooms with large glazing areas, where big windows might involve increased heat losses from the radiating surfaces of the radiator, thus generating higher operating costs. For this reason, they are often installed in offices, shops or banks. The typically small geometrical dimensions, especially the height, are another advantage. Owing to it, a radiator placed near a largely glazed wall neither obscures the view nor limits daylight lighting.

Figure 2.7 presents the view and structure of a small-height convector radiator suitable for mounting at the bottom of a display window. Figure 2.8 presents the view and structure of a climaconvector.

Taking account of possible applications, the most important advantages of convector radiators and climaconvectors are as follows:

– small unit mass,
– small geometrical dimensions,
– very low water capacity and small thermal inertia compared to panel radiators,

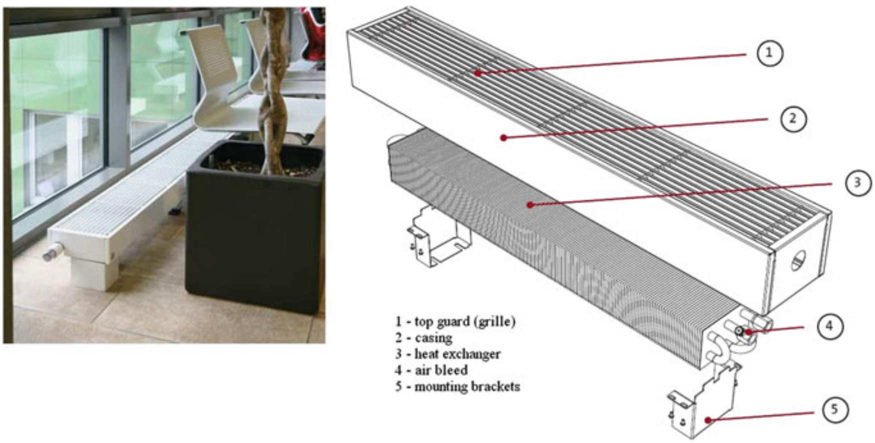

Fig. 2.7 Purmo Aura Comfort convector radiator [8]

– the room air high heating rate (in the case of climaconvectors),
– reduced share of radiation in the heat transfer process compared to other radiator types.

The disadvantages should also be considered in relation to requirements and possible applications. It appears that in this context the devices discussed in this section in fact have no downsides—they surpass plate and column radiators in every aspect. But if the issue is considered in relation to a typical home heating installation, some favourable characteristics of the device may be considered as disadvantages, the most important of which is the fact that enhanced convection causes a more intense lifting of the dust circulation (as discussed and verified experimentally in [11]) and a decrease in the radiation share. The former has a negative impact on hygienic conditions and the latter—on the thermal comfort sensation. Therefore, convectors and climaconvectors are rarely used in residential housing construction.

2.2.4 Canal Radiators

Taking account of the principle of their operation, canal radiators are in fact convector radiators. Like them, they may be made with a fan and as a cooling device. Their name is derived from the fact they are suitable for installation and operation in canals made in the floor. A metal trough specially designed for a given radiator is put in the canal, where the radiator is then installed. The entire structure is covered with a grille serving a decorative function and protecting the radiator from above.

Like convectors, such devices are used in rooms with higher aesthetic requirements and large glazed areas in internal walls. They are also similar in structure. Their heat exchange area is very well developed. Figure 2.9 presents the device structure and view.

Fig. 2.8 Purmo Vido climaconvector [8]

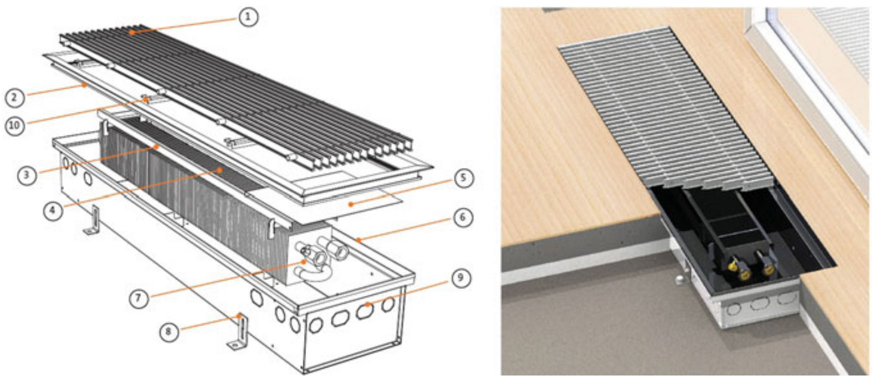

Fig. 2.9 **a** Purmo Aquilo FMK canal radiator (with no fan); Purmo Aquila F1T canal radiator (with a fan) *1* finishing grille, *2* finishing batten (optional), *3* forced-draught fan module, *4* plate-fin (lamella) heat exchanger, *5* metal sheet masking the installation connection, *6* radiator trough, *7* air vent, *8* fixing elements, *9* penetration for the installation ducts, *10* strengthening batten [8]

The canal radiator advantages are the same as those of convectors, and they should be considered in similar categories. An additional characteristic of the device resulting from its location is the possibility of creating an air curtain which effectively prevents the cold air inflow through cracks in the window joinery. However, this particular location also makes heat exchange difficult. As a result, the unit values of power of canal radiators are lower than those of comparably sized convector radiators. Moreover, being in-floor devices, canal radiators can mainly be mounted in the groundslab because due to the required installation depth they not always can be placed in intermediate floors.

2.2.5 Tube Radiators

Considering the ease of the manufacturing process, tube radiators are the simplest solution. Generally, they are divided into radiators made of smooth or finned tubes. The first solution is a steel tube, usually with a diameter included in the DN 10-DN 80 standard range. In the past these devices gained the greatest popularity in industrial facilities, sports halls, warehouses and spaces with a lower aesthetic standard. The tube radiators used in Poland were made with nominal diameters from the DN 40-DN 80 standard range.

A radiator made of a finned tube, referred to as finned-tube radiator or Favier radiator, is a development of the basic tube heating device. The finned-tube radiator was patented by Janusz Dżygadło, Bogdan Pietrzak and Roman Kwiatek of the “Metalowiec” work co-operative in Olsztyn. It has a metal ribbon wound onto and permanently joined to the tube surface.

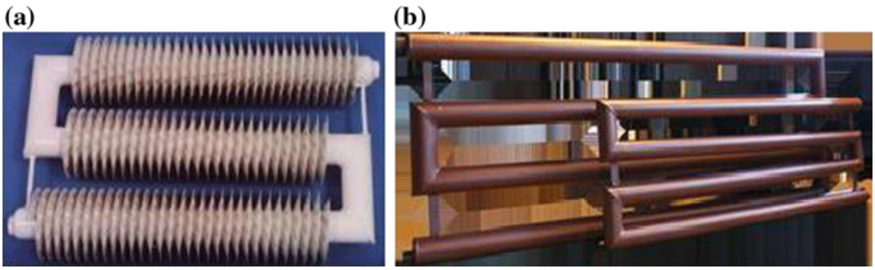

Fig. 2.10 **a** Finned-tube radiator. **b** Smooth-tube radiator [12, 13]

Tube radiators may make up sets of several rows placed one over the other. Popular smooth-tube and finned-tube radiators of the old type are presented in Fig. 2.10.

Tube radiators of the old type are more resistant to the effect of pressure and have the smallest hydraulic resistance, but they are very heavy and massive. In the case of finned-tube devices, it is very difficult to keep their external surface clean. Currently, they may be made as aesthetic thin-walled structures which are much lighter and which have interesting shapes.

State-of-the-art tube radiators are also made in the vertical form, as prismatic (single) or cylindrical (double, coaxial) tubes with a water jacket. Such solutions are presented in Fig. 2.11.

In radiators with coaxial tubes water flows between the cylinder internal and external wall. As a result, air may be heated not only by the tube external surface but also by the internal one as it passes through the tube. Using special plugs and stopping a selected number of ducts, it is possible to regulate the radiator thermal power and the share of convection in the heat exchange process. The cylindrical casing reduces the device capacity and thermal inertia.

Fig. 2.11 Vertical tube radiator [14]

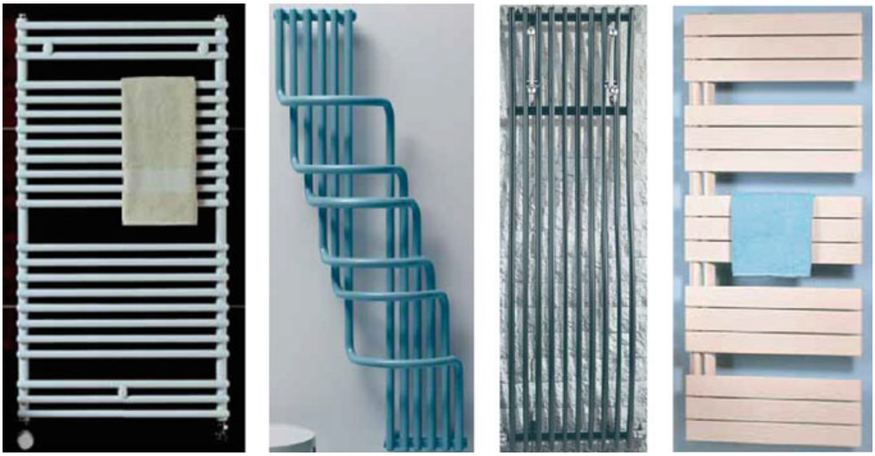

Fig. 2.12 Bathroom radiators [8]

Tube radiators, especially the ones made of smooth tubes, find application in rooms where low thermal powers are required and where a panel radiator selection is problematic, as well as in rooms characterized by difficult operating conditions, where radiators run the risk of being hit and damaged.

A special group of tube radiators are bathroom devices colloquially referred to as *ladders*. They are designed for operation in bathrooms, toilets and other rooms intended for people without outerwear. Their shape is also determined by utility needs because they are often used to dry towels or laundry. Apart from a classical *ladder*, with both ends of horizontal tubes connected to vertical ones, such radiators may be made in other shapes as decorative elements. Examples of such bathroom radiators are presented in Fig. 2.12.

All the types mentioned above are classified as convective radiators because convection dominates in the heat exchange process.

2.2.6 Surface Radiators

The surface radiator is a special heating device solution that needs to be discussed in greater detail due to the specificity of its structure, selection and sizing. In contrast to classical convector radiators, its calculation is closely related to the structure of the building partition the radiator is installed in, the way in which the partition is organized and the room purpose.

Surface radiators belong to the group of low-temperature heating systems. They are devices (or proper installations in fact) with large heating areas that use the building partitions in the heat transfer process. This section is focused on the underfloor radiator as the most common type of surface radiators.

2.2.6.1 Floor Heating Characteristics

As the requirements concerning thermal performance of buildings become stricter, the required design thermal powers of heating systems and radiators installed in them get smaller. Owing to that, it is possible to reduce their size or the temperature of their operation. Until recently designers usually assumed high supply temperatures of the order of 90 °C. The typical values today for classical convector radiators are included in the range of 70–80 °C. A reduction in the required unit heating power in buildings and, consequently, in the temperature of the installation operation makes it possible to use underfloor radiators which can independently satisfy the demand for thermal power without an excessive rise in the floor temperature. The supply temperature usually varies in the range of about 35–55 °C, which produces the temperature of the floor at the level of about 22–33 °C.

The sizing of this radiator type for design conditions is usually carried out for a slight drop in the water temperature of the order of Δt_w = 5–10 °C. Such values are much lower compared to classical convector radiators, which results from the fact that the highest possible homogeneity of the floor temperature field is required, i.e. the differences between temperatures of the floor individual fragments should be as small as possible. In order to achieve that, also the differences in temperatures in individual sections of the underfloor coil have to be possibly small.

Floor heating may be a very favourable alternative compared to classical convector radiators because this particular solution has a number of advantages. The basic one is that it ensures the highest thermal comfort of all types of heating systems now in use. This is the effect of a favourable temperature distribution with a very small vertical gradient, i.e. the highest temperature close to the floor and a slow vertical decrease in it, that may be obtained if underfloor heating is applied. Such a temperature distribution is closest to the model, most beneficial one in terms of the thermal comfort sensation. Classical convector radiators create an inverse temperature distribution. Forced air heating systems are the most unfavourable in this respect (cf. Fig. 2.13). Moreover, underfloor heating ensures a high convergence of the temperatures of air and of the partitions surrounding it, both vertically and horizontally. The effect is that heat losses to the environment are distributed uniformly in all directions.

Advantages and Disadvantages of Hydronic Underfloor Heating Systems

The underfloor radiator gives up much of its heat output through radiation. The actual share is difficult to assess precisely but it is estimated that it may reach 70% (50%, typically) [15]. Taking this into account and due to the fact that the radiator has a very large surface area of heat radiation, it is possible to lower the air temperature by about 2 °C, keeping the same value of operative temperature and the thermal comfort level [16]. This results in smaller heat losses due to the heat transfer through external partitions as well as smaller heat losses related to ventilation [17]. And this means lower operating costs compared to the case with typical

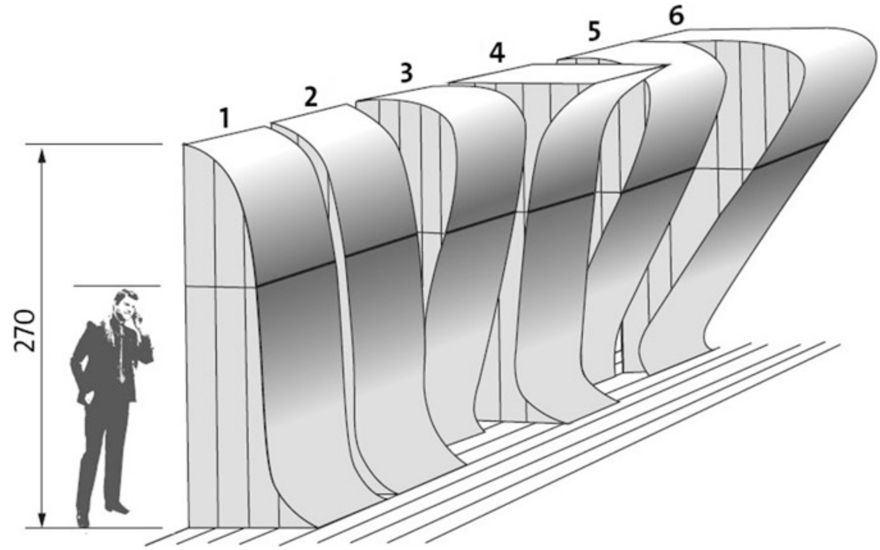

Fig. 2.13 Example vertical distribution of temperatures for different heating systems: *1* the most favourable for a human; *2* in underfloor heating; *3* in heating based on convector radiators mounted on external walls; *4* in ceiling heating; *5* in heating based on convector radiators mounted on internal walls; *6* in forced air heating [8]

convector radiators. Underfloor heating is also the most reasonable heating system to be used in high rooms. If convector radiators are used in them, heated air gathers under the ceiling, above the zone of human habitation, causing a thermal discomfort sensation. In order to improve the situation, the radiator power and temperature are then raised, which deteriorates hygienic aspects and increases operating costs. A similar situation occurs in large-sized rooms, where classical radiators, unable to ensure a uniform temperature all over the room, create local zones of warmer air. Giving up much less heat through convection, the underfloor radiator makes it possible to avoid such problems.

Another advantage of the underfloor radiator which results from the low operating temperature is the so-called self-regulation phenomenon. It consists of a strong feedback between the value of the heat flux given up to the room and the change in the room temperature. For example, if the radiator temperature is 26 °C, and the room temperature is 20 °C, a rise in the latter value by 3 °C will involve a twofold drop in the original temperature difference, which means approximately a twofold decrease in the exchanged thermal power. It can be noticed that the smaller the original temperature difference, the stronger the self-regulation effect, i.e. the smaller the risk of the room overheating if heat gains occur.

A low operation temperature also creates the possibility of effective use of alternative low-temperature energy sources, such as heat pumps, solar collectors, geothermal energy sources or gas-fired condensing boilers. All of them achieve high values of efficiency at low temperatures of operation. They are also characterized by higher values of energy and exergy efficiency compared to classical solutions, which allows a reduction in primary energy consumption [18, 19]. In addition, lower operating temperatures involve smaller transport-related heat losses in ducts, thus improving the system energy efficiency.

Underfloor heating systems also ensure high hygienic parameters of the room air because they do not cause dust lifting or circulation, and owing to the low temperature they do not make dust sinter and stick to heating surfaces. As a result, they diminish the risk of irritation to the eye and throat mucous membranes [16]. They also prevent the air ionization phenomenon arising due to contact of air with a metal surface with a high temperature. Systems where the heating surface is not made of metal and has a lower temperature are more favourable, and this is the case with underfloor heating systems [20].

However, these systems are not entirely free from disadvantages, and for this reason their popularity in certain types of buildings and rooms is limited. The biggest downside is the underfloor radiator very high mass, at least a few dozen times bigger compared to a convector radiator with a similar heat output. The resulting problem is very high thermal inertia and the fact that it is practically impossible to regulate power by means of typical quantitative regulation, i.e. by using automatic control valves. Qualitative regulation is also relatively ineffective in practice because the lowest temperature that may be set in a given circuit at the radiator inlet is the temperature at its outlet, which due to the radiator high thermal capacity is kept at a high level for a long time. Therefore, if heat gains (e.g. from people or solar exposure) occur in a given room, the radiator will continue to give up similar heat and the drop to the required power value will take several hours to achieve the required state long after the interfering signal (the heat gain) is stopped, even if the thermoregulator controlling the radiator operation responds promptly (which is practically impossible anyway). As a result, the room may be overheated for a long time, which will have a negative impact on thermal comfort and on operating costs. This effect may be minimized by lowering the radiator temperature and, thereby, the difference between this temperature and the temperature of the room. This, however, limits the unit heat output and requires that large areas of the radiator should be used. Nonetheless, the phenomenon described above may not be a nuisance for a long time of the installation operation. This is because only in design conditions, where the greatest thermal powers are required, do the highest temperatures of the radiator operation occur. However, design conditions prevail for just a few days at best, and frequently they do not appear in a given heating season at all. Practically then, the floor temperature will be only slightly higher than the indoor temperature and the described problem will be to a great extent compensated for by the self-regulation phenomenon.

The diagram in Fig. 2.14 illustrates changes in the floor temperature in the function of outdoor temperature.

Another problem related to the underfloor radiator is its high sensitivity to the heat resistance of the floor top (finish) layer that covers the layer where the coil is laid. The radiator parameters, the tube spacing, the length of the tubes and the

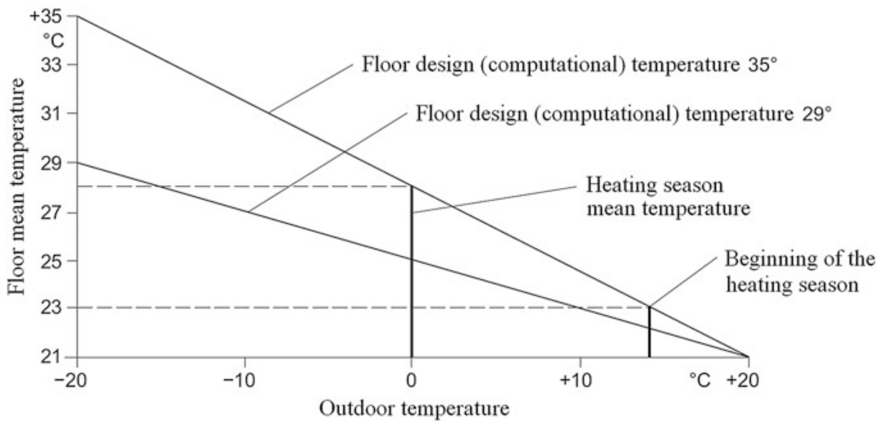

Fig. 2.14 Mean floor temperature of the underfloor radiator depending on outdoor temperature [21]

temperature of operation are calculated assuming a certain value of the resistance. Each change in its value involves a change in the heat output. If the initial thermal power needs to be restored, the supply temperature has to be altered. However, the values of this parameter are also included in a certain limited range resulting from other operating requirements concerning the installation elements, e.g. the boiler. For this reason, it always has to be checked whether a change in the top layer will not render achieving the radiator required thermal power impossible because sometimes the change cannot be fully compensated for by altering the supply temperature. Two alternative top layers are especially worth analysing: the carpet and ceramic tiles because they are characterized by significantly different heat resistance values and the use of a carpet substantially limits the underfloor radiator thermal power.

Another downside of underfloor radiators is the specific surface area that has to be ensured to achieve a given thermal power value. This may cause some practical problems because a change in the room original arrangement, for example by adding more furniture, may affect the heat exchange surface area and, thereby, the radiator power. The situation is then similar to the case where the owner wishes to change the radiator top layer.

For these reasons, underfloor radiators are most often installed in bathrooms and kitchens, where the top layer heat resistance is usually low (ceramic tiles instead of the carpet) and higher thermal inertia is permitted.

Another factor that may make the application of underfloor heating systems difficult is the limited heat output resulting from the fact that the floor temperature is limited to certain values due to health reasons and the thermal comfort sensation. Too high temperatures of surfaces that a human foot is continuously in contact with may lead to problems related for example to blood circulation. The difference between the temperatures of the floor surface and the room itself is the heat exchange driving force and any reduction in it involves a decrease in thermal power. For example, at the indoor temperature at the level of 20 °C and the recommended maximum value of the temperature of the radiator (calculated as the mean temperature of the radiator entire surface area) at the level of 26 °C (29 °C permissible, cf. sections below), assuming the surface film conductance value at the level of 10.7 $W/(m^2K)$, a unit heat flux is obtained of 64 W/m^2. This value is rather low. However, in view of the current legal regulations which aim to limit the energy consumption of buildings further and further, it is sufficient for newly built construction facilities in developed countries.

The limited carrying capacity is another limitation related to underfloor radiators. Therefore, they are not recommended for use in factory halls with heavy machinery or elements requiring foundation.

The underfloor radiator may also be troublesome in terms of hydraulic regulation. From the design requirement of a small drop in the water temperature it follows that in order to achieve the assumed heat output, the water mass flow has to be increased according to Eq. (3.43). Underfloor heating systems are characterized by high values of the flow resistance, which is the effect of the coil length on the one hand and of the large number of local obstacles (bends) on the other. As a result, a large drop in the water pressure arises, which has a negative impact on the regulation properties of the co-operating valve, reducing its total authority and deteriorating the regulation quality, as presented in [22]. Moreover, the large pressure loss creates the need to use a circulation pump with an appropriately high power, and this increases the electricity consumption and operating costs.

The costs of making an underfloor heating installation are higher compared to classical solutions with convector radiators.

To sum up, the following advantages of underfloor radiators may be distinguished:

- high share of radiation in the heat transfer process,
- favourable vertical temperature distribution,
- favourable values of the floor temperature,
- minimization of dust lifting,
- elimination of the risk of air ionization,
- minimization of the air temperature stratification and possibility of ensuring thermal comfort in high rooms,
- possibility of using low-temperature renewable energy sources effectively,
- lower operating costs.

The main disadvantages include:

- very large mass of the radiator and high thermal inertia,
- high water capacity,
- high hydraulic resistances,
- relatively high investment costs,
- limited heat output,
- the need to use relatively complicated regulation systems,

– no possibility of correcting the radiator structure without demolishing the floor,
– limited range of the heat output control,
– high sensitivity to the installation conditions and to the floor top layer type.

The Structure of Hydronic Floor Heating Systems

Standard EN 1264 [23] distinguishes four basic types of underfloor radiators, marking them as:

A pipes embedded in the screed layer over thermal insulation,
B pipes embedded in the upper part of the thermal insulation layer,
C pipes imbedded in the levelling screed layer under the separating layer,
D system with on-surface elements.

Additionally, the EN 15377 European standard [24], replaced by the ISO 11855 international standard [25], specifies the following types:

E pipes embedded in a massive concrete slab,
F capillary tubes embedded close to the radiator internal surface,
G pipes embedded in the wood floor structure.

The most common type A is divided into three sub-types depending on the pipe distance from thermal insulation, according to Table 2.1.

Standard EN 1264 [23] also specifies the calculation methodology for each of the types mentioned above. Figure 2.15 presents the structure of the A, B, C and D types of the underfloor radiator.

Underfloor heating systems may be made using:

– the wet technology,
– the dry technology.

In the wet technology, the pipes previously arranged with a specific pitch are fixed to the base and covered with a layer of screed (concrete) which the coil entire perimeter is in contact with and which distributes heat by means of conduction. It is thus a uniform solid structure that has to be destroyed if access to the coil has to be provided in the case of a failure. This type of radiators should be classed as Type A.

In the dry technology, the pipes are not embedded totally but they are laid in the layers in purpose-shaped grooves. In this technology pipes are often pushed into an aluminium sheet to improve the heat transfer to the layer above. Then the whole

Table 2.1 Sub-types of the Type A underfloor radiator

Radiator type	Pipe distance from insulation, mm
A1	<5
A2	5–15
A3	>15

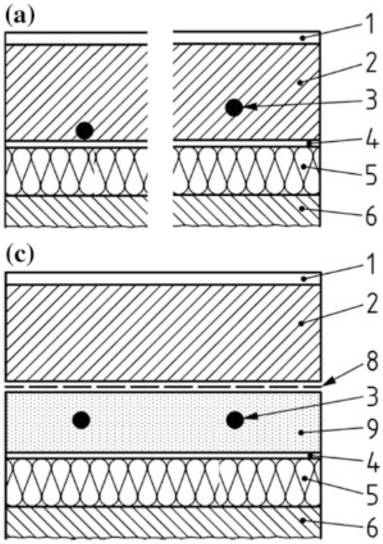

Fig. 2.15 Types of the underfloor radiator according to EN 1264. **a** Type A. **b** Type B. **c** Type C. **d** Type D: *1* top layer, floor covering; *2* load-bearing and heat-distributing layer (screed); *3* coil pipe (on-surface element in **d**); *4* vapour barrier; *5* thermal insulation; *6* load-bearing structure (floor, ceiling); *7* heat-distributing foil; *8* separating layer; *9* levelling layer [23]

structure is covered with screed. The heat transfer to this layer does not take place on the entire perimeter but through the pipe upper part mainly, and not only by means of conduction but also through convection. This makes it difficult to create appropriate mathematical models intended for the heat output calculation. Instead of screed, prefabricated slabs are sometimes used and laid on the layer with pipes. This is a simpler method that allows corrections and repairs of the coil if operating problems or failures occur. This type of radiators should be classed as Type B. Both solutions are illustrated in Fig. 2.16.

Underfloor heating systems are most often used in residential construction. In rich developed countries, such as Germany for example, the share of newly-erected residential buildings with heating installations based on this solution reaches as much as 50% [26]. Moreover, they find application in places where aesthetic factors play a major role, e.g. in hotels, conference rooms, religious buildings, museums or offices.

Fig. 2.16 An underfloor radiator made using the wet **a**, **b** and dry **c** technology [8]

Generally, the top layer of the underfloor radiator should be characterized by possibly low heat resistance. The recommended upper value is 0.15 (m^2K)/W [23]. Consequently, the preferred materials are clinker bricks, terracotta tiles, marble and granite, and not carpets, linoleum or wood parquets.

Maximum Temperature of the Heating Floor

The maximum heat output of an underfloor radiator at a given indoor temperature is conditioned by the heating floor temperature. This in turn depends on the room function, the time people spend in it and the type of used footwear [27]. The values of this parameter for people wearing light home shoes are given in the CEN CR 1752:1998 report [28], and, based on it, they are further specified by Standard EN 1264. According to the report, the following maximum temperature values are assumed:

– for rooms intended for permanent occupation by people without outerwear who do not do any continuous physical work, such as dayrooms, anterooms, kitchens, living rooms, offices, etc.: 26 °C. The value may be raised to 29 °C, but it should be noted that this leads to deterioration in thermal comfort conditions.

The report also indicates that the floor optimum temperature is about 23–24 °C because for this value the *PPD* index is the lowest (6%).

Similar values may be found in the archival PN-85/N-08013 Polish standard [29], which is a translation of Standard ISO 7730 now binding in Poland.

Moreover, according to Standard EN 1264, the following temperature values of the floor surface are assumed:

– for rooms with a raised temperature for people wearing no clothes such as bathrooms, shower rooms, dressing/locker rooms, swimming-pool halls, medical examination rooms, operating theatres, etc.: 33 °C,
– for the boundary zone (near-wall or near-window areas with a width of up to 1 m), where people stay for a short time: 35 °C.

Although the standard does not specify this particular case, for workplaces where people work in a standing position the floor maximum temperature is assumed at the level of 27 °C.

It is generally indicated that the surplus of the mean design temperature of the floor surface compared to the design temperature of a given area should not exceed 9 °C.

In the case of bare feet, it is not only the floor temperature that matters but also the material the floor is made of. When it comes to the thermal comfort/discomfort sensation, the latter is equally significant. It is well-known that in contact with the human skin "heavy" substances and materials with high density and thermal conductivity values create a feeling of lower temperature compared to "light" materials, even if in objective terms the material temperature is the same (e.g. water compared to air or ceramic tiles to carpets). This feeling is by no means subjective only because when two bodies are in contact, a resultant temperature settles that is determined by their following parameters: heat conductivity, density and specific heat. The parameter that relates the three quantities and conditions the material capacity for cooling is referred to as the thermal absorption coefficient expressed as follows:

$$b = \sqrt{\lambda \cdot \rho \cdot c}. \tag{2.1}$$

The temperature of two bodies upon contact may be expressed using the Van der Held formula (subscripts 1 and 2 denote the parameters of the first and the second body, respectively) [3, 4, 30]:

$$t_{\mathrm{st}} = \frac{b_1 \cdot t_1 + b_2 \cdot t_2}{b_1 + b_2}. \tag{2.2}$$

Consequently, the higher the thermal absorption coefficient of a given floor material, the closer the resultant temperature is to the material temperature upon the foot contact with it. All types of ceramic materials have much higher values of density, heat conductivity, specific heat, and—consequently—of the thermal absorption coefficient compared to carpets or other fabrics. Therefore, the thermal discomfort sensation upon a foot contact with a carpet is smaller than upon its contact with a "bare" floor with the same temperature.

Based on the relation presented above and knowing the permissible range of the resultant temperature variability as well as the foot temperature (about 31–32 °C), the permissible variability in a given material temperature may be established. Figure 2.17 presents temperature ranges for different materials of the finish layer which do not create a thermal discomfort sensation upon their contact with a bare foot. Table 2.2 lists the thermal absorption coefficient values for the most common materials used with underfloor heating installations. It is assumed that if the coefficient value is at the level of $b \leq 350$, the floor is felt as warm.

Irrespective of the required length, the underfloor radiator pipe may be laid in different ways. The most common configurations are the serpentine and the helical (spiral) arrangements. The arrangement type has an effect on the floor temperature distribution in the first place. At the same mean value, the temperature differences in the floor individual places may be considerable. Figure 2.18 illustrates the two arrangement types mentioned above with the floor example temperature distribution (in an enlarged scale).

As it can be seen, the pipe spiral arrangement is more favourable from the point of view of the floor temperature distribution. The parallel supply and return sections of the pipe make it possible to average and level the temperature. In practice, a denser pipe spacing is used in zones with higher heat losses or those exposed to an inflow of cold outdoor air, e.g. near the windows or balcony doors. In such cases the serpentine arrangement is sometimes applied with the coil beginning in these zones. As a result, the mean value of the floor temperature in these zones is raised

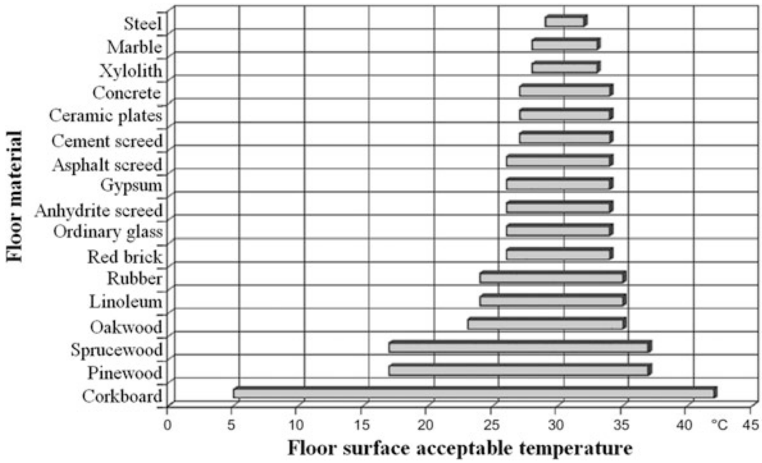

Fig. 2.17 Temperature ranges not leading to a thermal discomfort sensation upon contact with a bare foot for different materials of the underfloor radiator finish layer [31]

Table 2.2 Thermal absorption coefficient values for selected materials [32]

Type of material	Thermal absorption coefficient b, J/(m^2 s$^{0.5}$ K)	Type of material	Thermal absorption coefficient b, J/(m^2 s$^{0.5}$ K)
Corkboard	140	Anhydrite screed	1260
Sprucewood	280	Asphalt screed	1330
Oakwood	560	Gypsum	1120–1470
Rubber	560	Ceramic plates	1400
Xylolith	560	Cement screed	1190–1610
Linoleum	630	Artificial stone	2380
Marble	3010		

and a bigger heat flux is emitted. These places are referred to as boundary zones. The effect may be obtained using a single heating circuit (coil) or by adding a separate coil for the boundary zone, as illustrated in Fig. 2.19.

The technology of the radiator manufacture and the materials used in the process have to meet a number of other requirements unrelated directly to the operating principle or the way of calculating the heat output, such as durability, reliability and operational safety. The materials used to make the finish layer should be adapted for operation in raised temperatures and must not emit harmful volatile substances or change their geometrical dimensions in too large a range. The materials that satisfy the requirement are typically marked in trade using the symbols presented in

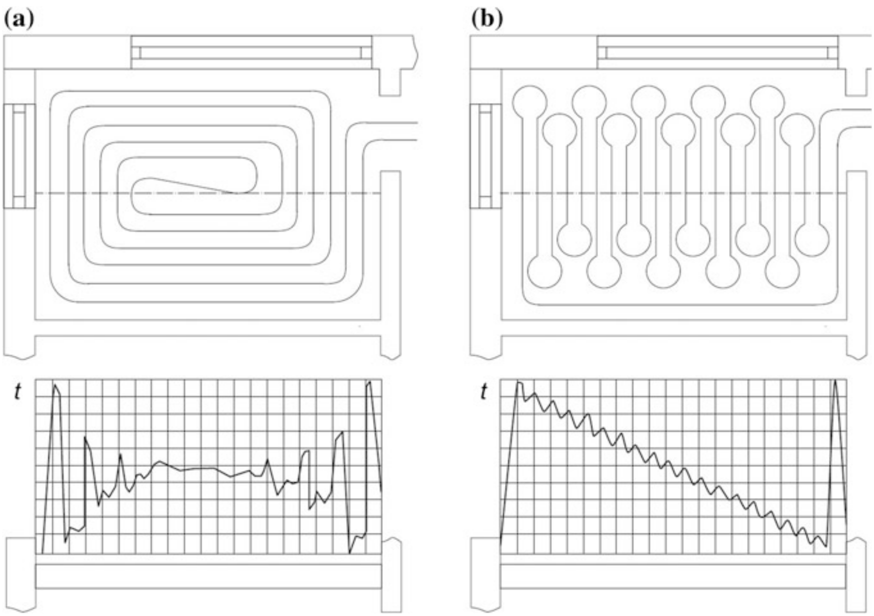

Fig. 2.18 Pipe layout and the floor temperature distribution: **a** spiral arrangement; **b** serpentine arrangement [32]

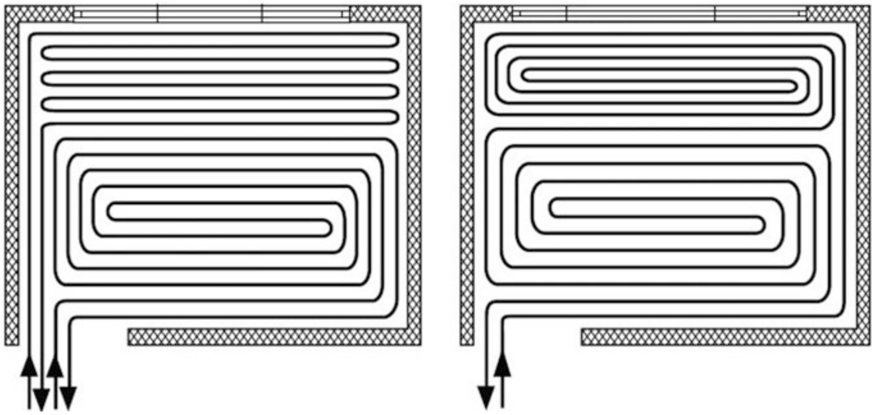

Fig. 2.19 Example arrangement of the underfloor radiator pipes with a boundary zone

Fig. 2.20. In particular, this concerns textiles with an addition of artificial materials, rugs, carpets, etc. Moreover, the floor should be made with elastic movement joints at the walls that will take in the changes in the radiator size caused by thermal expansion. These requirements are described in detail for example in [21, 23, 33–35].

(a) (b)

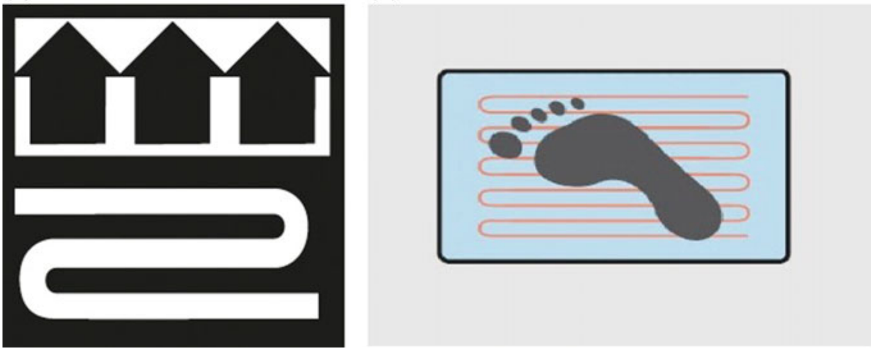

Fig. 2.20 Marking of the floor finish materials adapted for operation in raised temperatures: **a** for textiles; **b** for flooring panels [36]

2.2.6.2 Wall Surface Heating Characteristics

In terms of structure and the principle of operation, wall heating shares a number of characteristic features with the underfloor heating system. A wall radiator may also be made using the dry or wet technology. In the wet technology, the pipes are first fixed on the bearing structure (the wall) and then covered with plaster mortar with a binder in the form of gypsum, lime, cement, or plaster specially prepared by the wall heating manufacturer. The thickness of the covering layer is usually up to 30–40 mm. Reinforcement with fibreglass or metal mesh is often used to prevent the plaster cracking during the radiator operation, when the coil shrinks or expands due to variations in temperature. In the dry technology, the pipes are covered with ready-made gypsum-cardboard plates or gypsum fibreboards with grooves prepared for the coil. Alternatively, elements with a pre-installed coil may also be used. Such coils may be joined to each other to achieve the required thermal power. Both solutions of the wall radiator (i.e. installed using the wet and dry method) are presented in Figs. 2.21 and 2.22, respectively.

Like in the case of the underfloor radiator, the wall radiator share of radiation in the heat transfer process is bigger compared to convector radiators. The essential difference between the underfloor and the wall radiator is the maximum temperature of the heating surface and the unit heat output. The wall radiator may operate with higher values of the heating surface temperature (using an appropriately adapted material of the covering layer) because there is no direct contact with the human body. Part III of Standard EN 1264 specifies the permissible maximum temperature of the radiator surface at the level of 40 °C. Moreover, the layer covering the pipe is usually characterized by a lower heat resistance value compared to a typical underfloor radiator. For both these reasons the solution makes it possible to achieve higher unit thermal powers at a given temperature and mass flow of the working medium.

Fig. 2.21 Wall radiator made using the wet technology [37, 38]

Fig. 2.22 Wall radiator made using the dry technology [39, 40]

The wall radiator ensures a more favourable temperature distribution in the room than a convector radiator. However, it may not be as favourable as in the case of the underfloor radiator. If the radiator runs along the wall entire height, there is not such a clearly marked vertical temperature gradient with the maximum value at the bottom and the minimum one at the top (cf. Fig. 2.13). The temperature is much more levelled and almost constant. Designing the radiator only on a part of the height solves the problem. However, due to the wall radiator location, it is impossible to achieve a comfortable raised temperature of the floor, which in this case is comparable to the solution based on a classical convector radiator.

The wall radiator also allows a further reduction in the air temperature compared to heating installations based on convector or underfloor radiators. This is so because the solution makes it possible to achieve a large heating surface area which can “see” the room. Consequently, the share of radiation in the process of transferring the heat flux is high (it is estimated that it may be as high as about 90%). However, this is not related to higher values of the total surface film conductance compared to the underfloor radiator. According to Part V of Standard EN 1264, the value of this particular parameter for the wall radiator should be assumed at the level of $\alpha = 8$ W/(m^{2}K) instead of $\alpha = 10.8$ W/(m^{2}K) for underfloor heating. The effect of the moderate value of the surface film conductance combined with the rather high permissible value of the wall radiator surface temperature is that the device has the highest unit heat output of all the three systems of surface heating discussed herein.

In respect of the greater freedom of the room arrangement and the possibility of modifying the room equipment, the solution based on a wall radiator may sometimes be more flexible compared to the underfloor heating installation. However, all the room equipment (in this case: wardrobes, sofas, pictures, curtains, etc.) also need to be taken into consideration at the radiator design stage. The potential differences arising later on may make it impossible to achieve the preset thermal parameters.

Due to the smaller mass of elements where the heating pipe is located, the wall radiator is characterized by a lower capacity and thermal inertia than the underfloor radiator. Like the underfloor radiator, the wall radiator minimizes dust circulation and does not make dust sinter and stick to its heating surfaces. It also prevents air ionization.

If the radiator is installed on an external wall, an essential feature of wall heating is the occurrence of increased heat losses to the environment compared to a convector radiator. Using the wall heating solution, efforts should be made to achieve a possibly high value of heat resistance of the layer under the pipe, which practically translates into a thicker insulation layer.

2.2.6.3 Ceiling Surface Heating Characteristics

It is believed that ceiling heating was invented by Englishman A. H. Baker, who obtained a patent for his invention in 1907 and then sold his rights thereto to the

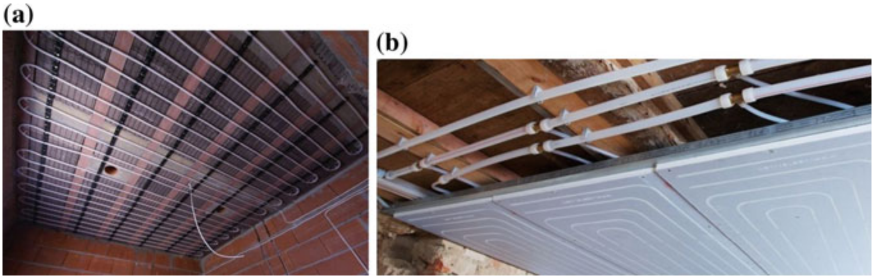

Fig. 2.23 A ceiling radiator made using the wet **a** and dry **b** technology [41, 42]

R.H. Crittall company, which implemented the solution into the heating practice [3, 4].

The ceiling radiator may be described by the same structural features as those used for the surface radiators characterized above. The main difference is that in this case even more than 90% of the overall thermal power is given up by means of radiation. Increasing the share of radiation in the heat transfer process at the expense of convection, the surface orientation (horizontal, downwards) results also in a reduction in the total surface film conductance value, which according to EN 1264 (Part V) should be $\alpha = 6.5$ W/(m^{2}K). Despite the higher share of radiation and due to its location, the ceiling radiator is characterized by the least favourable temperature distribution in the room, with a gradient opposite to the case with the underfloor heating system (cf. Fig. 2.13). According to EN 1264 (Part III), the radiator surface maximum temperature may total 29 °C. Combined with the low value of the surface film conductance, this gives the smallest unit heat output of all the types of the surface radiators presented herein. However, one essential advantage of the ceiling radiator is the almost absolute freedom of the room arrangement and the possibility of introducing any changes thereto during the radiator operation with no impact on the radiator thermal power or the thermal parameters of the room. The structural solutions of the ceiling radiator are presented in Fig. 2.23.

To sum up, the following advantages of wall and ceiling radiators may be distinguished:

- high share of radiation in the heat transfer process,
- favourable vertical temperature distribution (in the case of wall heating only),
- favourable values of the floor temperature,
- minimization of dust lifting,
- elimination of the risk of air ionization,
- possibility of using low-temperature renewable energy sources effectively,
- lower operating costs,
- relatively small capacity and thermal inertia compared to the underfloor radiator,
- high unit heat output (in the case of the wall radiator).

The main disadvantages include:

– relatively big capacity and thermal inertia compared to the convector radiator,
– high water capacity,
– high hydraulic resistances,
– relatively high investment costs,
– limited heat output (in the case of the ceiling radiator),
– rather unfavourable vertical temperature distribution, especially in the case of the ceiling radiator.

Like in the case of underfloor radiators, the requirements concerning the structure, installation and putting these radiator types into service are laid down in Standard EN 1264.

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