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Radiant Floor Heating In Theory and Practice

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During the last two decades, radiant floor heating applications have increased significantly. In Germany, Austria and Denmark, 30% to 50% of new residential buildings have floor heating. In Korea, about 90% of residences are heated by underfloor systems.

Around 100 B.C., Koreans used exhaust smoke from a fireplace to heat a stone floor. Smoke was conveyed from a fireplace (used for cooking) under the floor slab to an opposite wall, where the smoke was exhausted upwards in the wall like a chimney. In this way, the mass of the floor slab also was used as thermal storage. During this time, the Romans also were using this type of heating.

Architect Frank Lloyd Wright introduced floor heating to the United States in his Usonian houses in the 1930s. Circulating water in steel pipes provided heat distribution.

In the 1950s and 60s, floor heating installations using steel or copper pipes were installed in middle Europe. Unfortunately, at this time, buildings were not well insulated so very high floor temperatures were required to heat the houses, which gave floor heating a bad reputation. Then, at the end of the 1970s, the introduction of plastic pipe for floor heating prompted the system to become standard, especially in Germany, Switzerland, Austria and the Nordic countries. Today, plastic pipes of the PEX-type are mainly used.[1]

Floor heating is mostly used in residential buildings. However, in Europe it is also widely used in commercial and industrial applications. This article gives an overview of issues related to floor heating and discusses how a radiant underfloor system may be used for cooling.

Thermal Comfort

To provide an acceptable thermal environment for the occupants, the requirements for general thermal comfort (PMV-PPD, operative temperature[2]) and local thermal comfort (floor temperature, vertical air temperature differences, radiant temperature asymmetry, draft) must be taken into account.

Operative Temperature

The two main parameters for providing acceptable thermal conditions are air temperature and mean radiant temperature. The combined influence of these two temperatures is expressed as the operative temperature. For low air velocities (<0.2 m/s [40 fpm]), the operative temperature can be approximated with the simple average of air and mean radiant temperature. This means that air temperature and mean radiant temperature are equally important for the level of thermal comfort in a space.[3,4]

For a radiant heating system, an important factor is the angle factor between the occupants and the radiant heat source or sink. This factor depends on the distance between a person and the surface, and the area of the surface. The center of a seated person is only 0.6 m (2 ft) from the floor, while the distance to the ceiling is 1.8 to 2.1 m (6 to 7 ft). Therefore, the floor normally has the highest angle factor of all surfaces (walls, ceiling, windows, etc.) to the occupants.

For a person positioned in the middle of a 6 by 6 m (20 by 20 ft) floor, the angle factor is 0.40 for sedentary occupants and 0.37 for standing occupants. If the floor surface temperature is changed by 5 K (9°F) and all other surface temperatures are assumed to be unchanged, then the mean radiant temperature will change by 2 K (3.6°F). The operative temperature will change by 1 K (1.8°F). Stated another way, a 5 K (9°F) change of the floor surface temperature will have the same effect as changing the air temperature by 2 K (3.6°F).

In comparison, the angle factor to a ceiling is 0.15 to 0.20, which means one degree change of the floor temperature will have 2.5 times the effect on the mean radiant temperature (and operative temperature) than a change of the ceiling temperature.[5]

Compared to a 100% convective heating system (warm air heating), a floor heating system can reach the same level of operative temperature at a lower air temperature (*Figure 1*[5]). The transmission heat loss depends partly on the convective heat exchange between room air and external surfaces and partly on the radiant heat transfer between the external surfaces and the other surfaces in the space.

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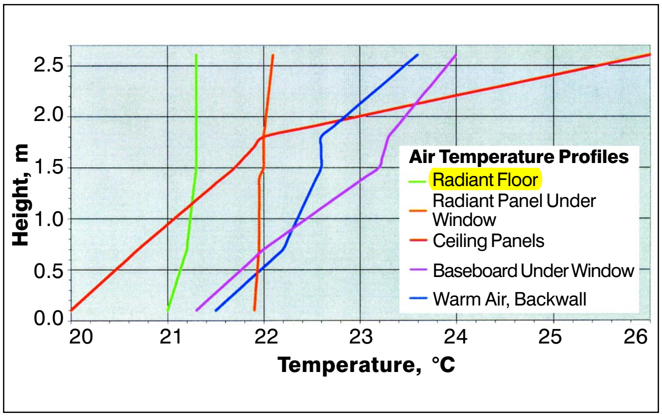

Figure 1: Vertical air temperature differences measured in a test space for different heating systems. Heat flux was 50 W/m². [7,8]*

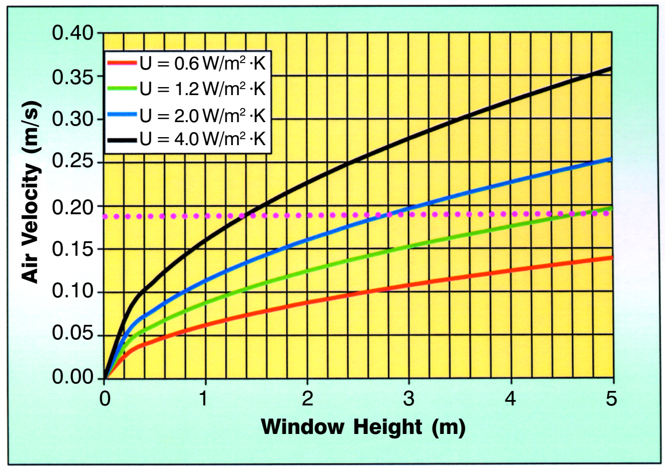

Figure 2: Downdraft from cold surfaces.*

The reference temperature for the transmission heat loss is then closer to the operative temperature than to the air temperature. Therefore, there will not be any significant reduction of transmission heat loss. It will, however, result in a lower ventilation heat loss. In buildings with high ventilation rates, such as industrial storage areas, hangars, etc., this has a significant influence on energy consumption and supports the use of radiant heating. In modern well-insulated and tight residential buildings, this effect is minor because the difference between mean radiant and air temperature is relatively small.

Differences between several types of heating systems have been studied.[6,7,8] In general, the results show that most heating systems are capable of providing an acceptable thermal environment. By increasing insulation of buildings (walls/windows), and thus, decreasing heat loads, the difference between systems is less.

Floor Surface Temperature

In international standards,[2,4,9] a floor temperature range of 19°C to 29°C (66°F to 84°F) is recommended in the occupied zone for rooms with sedentary and/or standing occupants wearing normal shoes. This is a limiting factor for the capacity of floor systems. For heating, the maximum temperature is 29°C (84°F), and for cooling, the minimum temperature is 19°C (66°F). In the European standard,[9] it is acceptable to use 35°C (95°F) as the design floor temperature outside the occupied zone, i.e., within 1 m (3 ft) from outside walls/windows. In spaces where occupants may have bare feet (bathrooms, swimming pools, dressing rooms), the optimal floor temperature for comfort also depends on the floor material.[10]

Vertical Air Temperature Difference

One of the main features of radiant floor heating is the uniform temperature conditions from floor to ceiling. Measurements from a test room[7,8] are shown in *Figure 1* for four types of heating systems: radiant floor heating, low-temperature panel heater under a window, baseboard under a window and warm air heating with the supply at the back wall. Floor heating and the large wall panel heater under the window have a uniform temperature profile. The more convective systems have larger differences. The basis for the measurements was a 22°C (72°F) operative temperature at 1.1 m (3.6 ft) level.

Figure 1 shows that the 22°C (72°F) operative temperature, using floor heating, was obtained at 1 K to 1.5 K (1.8°F to 2.7°F) lower air temperature than the other systems. The measurements are shown for a heat load of 50 W/m². For more convective systems, the temperature profile becomes less uniform. In high ceiling spaces, such as industrial workplaces, atriums, and hangars, increased stratification significantly increases heat loss because of the increase in average space temperature.

Radiant Temperature Asymmetry

As shown in the previously mentioned studies and as demonstrated by Olesen,[5] there are seldom problems with radiant asymmetry from cold windows in modern buildings. Using ANSI/ASHRAE Standard 55-1992, *Thermal Environmental Conditions for Human Occupancy*[4] and the *ASHRAE Handbook—Fundamentals,*[3] it is possible at the design stage to evaluate the risk for discomfort due to radiant temperature asymmetry.

Draft

Downdraft from cold surfaces (windows) is another factor that may cause discomfort. On the basis of a calculation method,[5,11] the relation between the window height, U-value for the wall/window, outside temperature and the maximum air velocity can be determined.

Assuming an airflow with a low turbulence intensity (10% to 20%) and an air temperature of 21°C (69.8°F), the recommended maximum acceptable air velocity in existing standards is 0.18 m/s (36 fpm).[2,3] *Figure 2* shows the relation between window U-value, window height and resulting maximum air velocity in the occupied zone by –12°C (10.5°F) outside tem-

* m ÷ 0.3048 = ft; (°C × 1.8) + 32 = °F; m/s ÷ 0.00508 = fpm

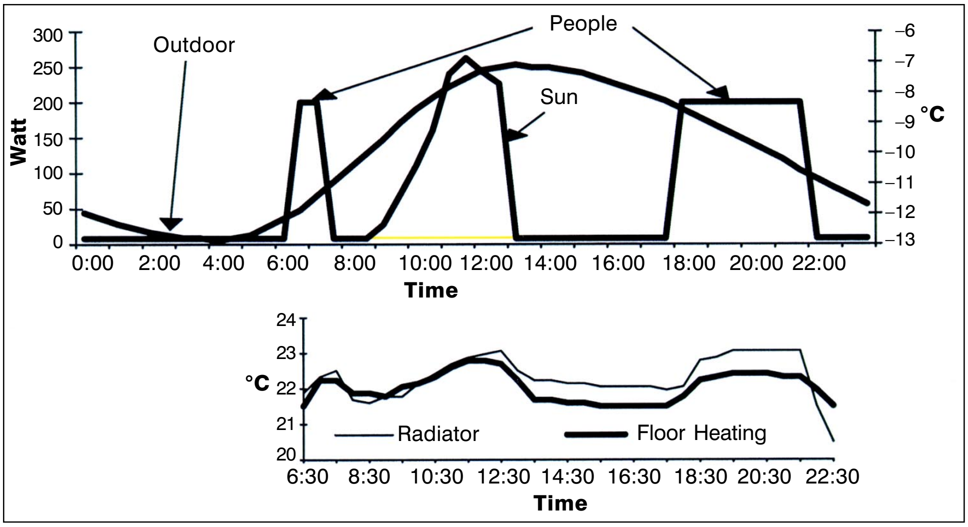

***Figure 3:** Variation in outside temperature, load from occupants, lighting and sunlight together with the variation in the room temperature (equivalent/operative temperature) for two heating systems.[18]**

perature. If the air velocity is lower than the 0.18 m/s (36 fpm) at design conditions, it is unnecessary to compensate with heating below the window. If needed, floor heating can be designed with a higher surface temperature at the wall/window (smaller pipe distance, higher water temperature).

Indoor Air Quality

The higher surface temperatures on windows and walls in well-insulated buildings, or the higher mean radiant temperature in buildings with radiant floor heating, means that the air temperature can be kept lower than in "standard" houses. This has the advantage that the relative humidity in winter may be a little higher. Also, studies show[12] that people perceive air quality to be better at lower air temperatures. Due to the higher surface temperatures, there is less chance for condensation and mold growth. Floor heating also prevents cold corners.

The German Allergy and Asthma Association[13] has produced a study that shows that floor heating reduces the favorable living conditions for house dust mites compared to other heating systems. Higher temperatures in carpets and mattresses decrease the relative humidity. Also, because mites seek the upper areas, they are more easily removed by vacuum cleaners. Another study found a lower level of dust mites in Korean houses than in Japanese houses.[14] This was attributed to the same effect, but was not directly verified.

Radiant heating systems result in less transportation of dust compared to convective heating systems. Also, floor heating does not require cleaning heat emitters. Carpets are not as necessary when using floor heating, which eliminates a source for emitting pollutants and a sink source. This is especially helpful for people with allergies.

Heating and Cooling Capacity

The capacity of a floor system depends on the heat exchange between the floor surface and the space (convective and radiant heat exchange coefficient), the heat conduction between the floor surface and the tubes (floor surface material, type of concrete, type of floor system, slab thickness, spacing between tubes) and the heat transport by water (water flow rate, temperature difference between supply and return). In the *ASHRAE Handbook—HVAC Systems and Equipment* (Chapter 5) and in the European standard for floor heating,[9] a method is given to calculate the heating capacity of a floor system. The heat exchange coefficient at design conditions is 11 W/m²·K. At smaller temperature differences between floor surface and space, this will decrease to about 9 W/m²·K. Of the total heat exchange, more than half is due to radiation (~5.5 W/m²·K). The maximum capacity in the occupied zone is about 100 W/m² (29°C [84°F]) floor temperature, 20°C (68°F) room temperature. As mentioned earlier a higher floor temperature (35°C [96°F]) may be used within 1 m (3 ft) from the outside walls/windows. A 20°C (68°F) room temperature results in a heat output of 165 W/m². If the depth of a normal room is assumed to be 4 m (13 ft), the average heat capacity is 116 W/m² ([165 + 3 × 100]/4). This maximum heating capacity is independent of the type of floor covering (tiles, wood, carpet). The required water temperature to obtain the maximum heating capacity is, however, dependent on the thermal resistance of the floor covering and other factors such as system type and pipe spacing. The standard lists factors to account for these parameters.

Table 1 shows the influence of floor covering on the required water temperature at different heating demands. These values are for a floor system with pipes embedded in screed. For other systems with higher thermal resistance between the pipes and floor surfaces even higher water temperatures are required.

The heat exchange coefficient by floor cooling is only 7 W/m²·K. In most buildings a maximum cooling capacity at 26°C (78.8°F) room temperature and 20°C (68°F) floor temperature is then 42 W/m². Direct sunlight on the floor (as in atriums, airports, entrance halls) can cause the cooling capacity to be higher than 100 W/m².[16,17]

Design

The main design parameters are pipe distance, water flow rate (temperature difference between supply and return) and piping layout. A zone with a higher surface temperature at the outside wall is obtained by including a separate pipe circuit at higher water temperature or shorter pipe spacing (< 0.1 m [0.3 ft]). It can also be obtained by running the supply pipe first along the outside wall with a shorter pipe distance, and in the rest of the space the pipe distance is bigger and the supply and return will run parallel. A water flow rate in a floor heating system often is based on a water temperature difference of 10 K (18°F) between supply and return. For the room with the highest load, it is recommended to use only a 5 K (9°F) difference. This increases the average water temperature and then the heating capacity. To avoid pressure drops that are too high, the pipe circuits must be shorter.

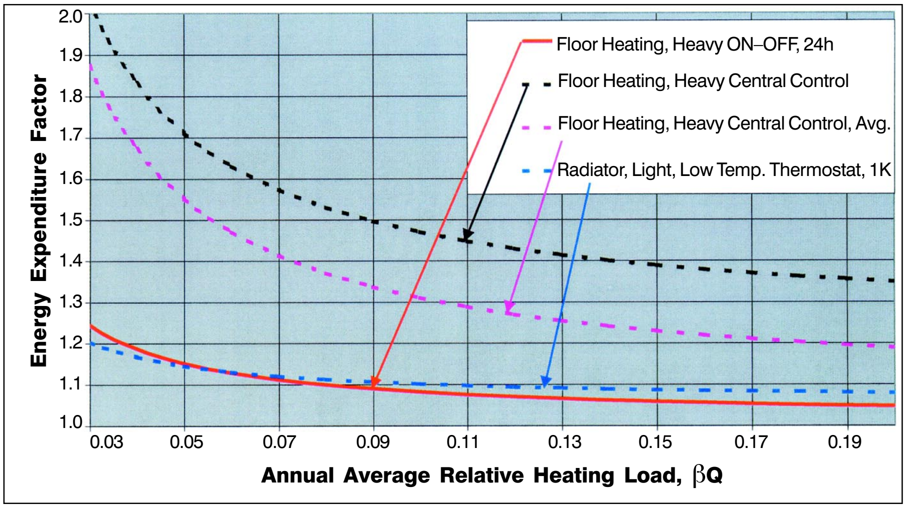

***Figure 4:** Relation between relative heat load and energy expenditure factor for different control strategies. The energy expenditure factor is the additional heat loss compared to an ideal control.*[19,20]

For maximum capacity, it is important to avoid floor coverings with a high thermal resistance such as heavy wall-to-wall carpets. This increases the required water temperature and then also the back losses to ground or unheated space. Also, higher water temperature reduces the efficiency of the heat generator (condensing boiler, heat pump).

Control

The main thermal comfort problem, which may occur in well-insulated buildings, is large variations in the room temperature due to changes in internal loads from occupants, lighting, equipment or direct sunlight. The low heat loss in well-insulated buildings means that changes in internal loads have a higher impact on the room temperature than in buildings with standard insulation. The influence depends on the thermal mass of the building and the controllability of the heating system. As floor heating systems often have a higher mass compared to other heating systems, it is often claimed that using floor heating means a greater risk for overheating and additional heat loss. However, several studies have found the opposite to be true.

Variation in the outdoor temperature is controlled for with an outside temperature sensor. With floor heating, this is normally done by changing the water temperature (average of supply and return water temperature) according to the outdoor temperature and a heating curve. For an efficient outside temperature control, it is important that this heating curve is carefully selected to account for the type of building (mass, heat loss) and the difference in heat required by different rooms. Sunlight and internal loads may have a high impact on room temperature requiring a reduction or increase in the heat output.

Some of the controllability depends on the thermal mass of the building and the system. For a low-temperature heating system, such as floor heating, a significant effect is the so-called "self control" caused by the very small temperature difference between room and heated floor. A small increase in room temperature will significantly decrease the temperature difference between floor and space and then decrease the heat output from the heated floor. The control is further improved by individual room thermostats that, based on room temperature, control the water flow rate individually to each room. The self-control depends on the temperature difference between room and floor and on the difference between the room and the water temperature. *Table 1* shows the percentage decrease in the heat emitted from the floor by a 1 K (1.8°F) increase in the room temperature. A well-insulated house has, on average, a heat load of 10 to 20 W/m² for the heating season. For these types of houses, the self-control effect corresponds to 30% to 90% (*Table 1*).

In an experimental study,[18] the controllability of a standard floor heating systems with tubes embedded in concrete was compared to a low temperature radiator system. A low thermal mass test room was exposed to variations in outdoor temperature, occupant load and sunlight (*Figure 3*). The variation in internal loads corresponded to about one-third of the heat loss of the test room. The results showed that, for both heating systems, the controls easily kept the room temperature within acceptable limits. There was no difference between the two systems. This self-control is only valid for hydronic floor heating systems and not electrically heated floor systems.

In an extensive study performed as basis for the new German energy code for buildings, the controllability of several types of heating systems was studied by detailed dynamic computer simulations. The results are now included in a new German standard (DIN 4701-10) for heating system performance and in a guideline from VDI-TGA.[19] *Figure 4* show the advantage of controlling the average water temperature (supply-return) instead of the supply temperature. Most importantly, *Figure 4* shows the energy advantage of using an individual room control. The studies showed a 15% to 30% energy savings by using an individual room control compared to a central control only.

Table 1: Floor temperature, average temperature of heating medium and the effect of self-control of radiant panel system in percent.

Average Heating Load Flux W/m²	Required Floor Temperature (at 20°C [68°F] Room Temperature) °C (°F)	Average Temperature of Heating Medium		% Decrease of Heat Output by 1 K (1.8°F) Increase of Room Temperature Reference Temperature		
		Tile 0.02 m²·K/W, °C (°F)	Carpet 0.1 m²·K/W, °C (°F)	Floor Surface %	Water	
					Tile %	Carpet %
80	27.3 (81.1)	31.9 (89.4)	38.4 (101.2)	14	8	5
40	23.9 (75.0)	26.2 (79.2)	29.4 (84.9)	26	16	11
20	22.1 (71.8)	23.3 (73.9)	24.9 (76.8)	48	30	20
10	21.1 (70.0)	21.7 (71.1)	22.5 (72.5)	91	59	40

The additional energy consumption in *Figure 4* is given as a relation to an ideal control with no system mass, energy expenditure factor. The figure shows this additional energy consumption as a function of the relation between design heat load and heating required. A low factor (~0.08) corresponds to a low energy house where the internal loads from occupant, light and sunlight significantly reduces the heating required. An existing house would have values higher than 0.20.

Figure 4 also shows a floor heating performance that is as good or better than a low-temperature radiator controlled by a thermostat valve.[20]

If night setback is used with floor heating, it is recommended to use boost heating in the reheat period in the morning to increase the performance. Reheating using a floor heating system must start earlier in the morning (than with a warm air system), however, the system can then be turned off earlier in the evening.

Due to the improved comfort when using individual room control and the possible energy savings, the installation of individual room temperature controls is recommended. Individual room controls are required for all types of heating systems in many European countries.

Besides the energy benefits, it is essential for thermal comfort for occupants to be able to individually adjust the temperature setpoint from room to room. Energy savings from using night setback in residential buildings is relatively low due to the high thermal insulation standard in new houses.

For the control of a floor cooling system, the dew point in the space must also be taken into account.[20]

Energy

The main purpose of increased insulation is to lower annual energy consumption. In addition, the supply, distribution, and emission of the heating system must be optimized. The differences in heat losses by heat emission of different types of systems (radiators, convectors, warm air, floor heating, ceiling heating) are small in well-insulated houses.[6,7,8] Using low-temperature heating is beneficial regarding distribution losses and efficiency of heat generation. The highest efficiency of boilers, especially modern condensing boilers, is obtained by floor heating. Also, the efficiency of heat pumps or solar collectors is much higher with a low-temperature heating system such as floor heating. Because the floor system is a high-temperature cooling system, it enables a higher efficiency for a reversible heat pump or chiller. As the ground temperature often is around 10°C (50°F), it also is possible to cool a floor directly from a ground heat exchanger (pipes embedded in the ground or foundation) without the use of a heat pump.

A floor cooling system can be used in combination with an air system. The floor system takes care of most of the sensible load, while the air system takes care of the latent load. At the same time, the dew point in the space will be lowered resulting in a higher cooling capacity for the floor system. Also, the high return water temperature (18°C to 20°C [64.4°F to 68°F]) of the floor system increases the efficiency of a refrigeration machine.

Installations and Costs

In countries where hydronic heating, and especially floor heating, is a small part of the market, installers or builders do not yet have the sufficient experience to make sound installations. Therefore, suppliers must guide and train installers. In Europe, hydronic heating has been used for several decades, so most installers and builders are familiar with installation issues.

There is little published information on cost comparison. A recent study in Germany,[21] asked several installers to bid on a residential project with radiators and with floor heating. Overall, the difference was within ±10%, but several installers charged a higher overhead for floor heating, because they could sell it as a more comfortable and energy efficient heating system.

Conclusions

- The advantages of hydronic radiant floor heating include the efficient use of space and that cleaning is not required. Also, the system does not produce noise, cause drafts or use ducts. The system has uniform temperature distribution and is a low-temperature heating system.
- In a radiant floor heating system, the required operative temperature may be obtained at a lower indoor air temperature. This reduces ventilation heat loss compared to more convective heating systems. The transmission heat loss is more related to the operative temperature and is more or less the same for convective and radiant systems.
- Well-insulated buildings require an efficient control for variations in internal loads from occupants, lighting and direct sunlight. The combination of the self-control of floor heating systems combined with a room thermostat makes an efficient control for variations in internal loads even in well-insulated buildings.
- Floor heating increases the efficiency of heat generators due to the low water temperatures used.

• A hydronic floor cooling system provides sensible cooling without generating noise or drafts.

• The maximum cooling capacity is for most spaces less than 50 W/m². In spaces with direct sunlight on the floor, the cooling capacity is significantly higher.

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