Performance of Radiant Heating Systems of Low-Energy Buildings

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Abstract. After the introduction of plastic piping, the application of water-based radiant heating with pipes embedded in room surfaces (i.e., floors, walls, and ceilings), has significantly increased worldwide. Additionally, interest and growth in radiant heating and cooling systems have increased in recent years because they have been demonstrated to be energy efficient in comparison to all-air distribution systems. This paper briefly describes the heat distribution systems in buildings, focusing on the radiant panels (floor, wall, ceiling, and floor-ceiling). Main objective of this study is the performance investigation of different types of low-temperature heating systems with different methods. Additionally, a comparative analysis of the energy, environmental, and economic performances of floor, wall, ceiling, and floor-ceiling heating using numerical simulation with Transient Systems Simulation (TRNSYS) software is performed. This study showed that the floor-ceiling heating system has the best performance in terms of the lowest energy consumption, operation cost, CO₂ emission, and the nominal boiler power. The comparison of the room operative air temperatures and the set-point operative air temperature indicates also that all radiant panel systems provide satisfactory results without significant deviations.

1. Introduction

Buildings are an important part of European culture and heritage, and they play an important role in the energy policy of Europe. Energy consumption patterns worldwide reveal that buildings are the greatest energy consumer, consuming approximately 45% of energy, followed by industry and transportation consuming 20% [1]. Of the total energy consumption of a building, approximately 54% represents heating, and to cover this energy demand, great quantities of fossil fuel are burned, which generates considerable carbon dioxide (CO₂) emissions [2].

Because of the reduction of the world fossil fuel reserves and strict environmental protection standards, one main research direction in the construction field has become the reduction of energy consumption, including materials, technology, and building plans with lower specific energy need, on one hand, and equipment with high performance on the other hand.

To distribute the heat in buildings can be used a hydronic system (radiant panels and hot water radiators) or a central forced-air system. The use of surface heating systems is increasing in Europe, but however it is still much less than the use of hot water radiators [3].

After the introduction of plastic piping, the application of water-based radiant heating with pipes embedded in room surfaces (i.e. floors, walls and ceilings), has significantly increased worldwide. Earlier applications of radiant heating systems were mainly for residential buildings because of the
comfort and free use of floor space without any obstruction from installations. For similar reasons, as well as possible peak load reduction and energy savings, radiant systems are widely applied in commercial and industrial buildings. Additionally, interest and growth in radiant heating and cooling systems have increased in recent years because they have been demonstrated to be energy efficient in comparison to all-air distribution systems [4].

There are many papers dealing with investigations of low-temperature radiant systems and their comparison with other heating systems regarding energy consumption and obtained thermal comfort. Chen [5] compares the thermal comfort and the energy consumption among a ceiling radiant heating system, a radiator heating system, and a warm-air heating system and concluded that the radiant heating system uses 17% more energy than the other two systems. Steiu [6] found that the operative energy consumption by panel systems is 30% lower than that of classic heating systems. Bojic et al. [7] demonstrated that wall panel heating systems with proper thermal insulation have 28% lower primary energy consumption than that of radiator heating system.

This paper briefly describes the heat distribution systems in buildings, focusing on the radiant panels (floor, wall, ceiling, and floor-ceiling). Main objective of this study is the performance investigation of different types of low-temperature heating systems with different methods. Additionally, a comparative analysis of the energy, environmental, and economic performances of floor, wall, ceiling, and floor-ceiling heating using numerical simulation with Transient Systems Simulation (TRNSYS) software is performed.

2. Radiant heating systems

In low-energy buildings, the low-temperature heating system usually works with a supply water temperature below 45 °C [8]. Embedded radiant systems are used in all types of buildings. Radiant heating systems supply heat directly to the floor or to panels in the wall or ceiling of a house. Hydronic (liquid based) systems can use a wide variety of energy sources to heat the distribution liquid, including solar water heaters, standard gas- or oil-fired boilers, wood-fired boilers, or a combination of these sources.

Radiant heating application is classified as panel heating if the panel surface temperature is below 150 °C [9]. In thermal radiation, heat is transferred by electromagnetic waves that travel in straight lines and can be reflected. The water temperatures are operated at very close to room temperature and, depending on the position of the piping, the system can take advantage of the thermal storage capacity of the building structure.

Figure 1 shows the available types of embedded hydronic radiant systems [10]. These systems are usually insulated from the main building structure (floor, wall, ceiling), and the actual operation mode (heating/cooling) of the systems depends on the heat transfer between the water and the space.

![Figure 1. Examples of water-based radiant systems](image)

Panel heating provides a comfortable environment by controlling surface temperatures and minimising air motion within a space. A radiant system is a sensible heating system that provides more than 50% of the total heat flux by thermal radiation. The controlled temperature surfaces may be in the floor, walls, or ceiling, with the temperature maintained by circulation of water or air.
The radiant heat transfer is, in all cases, 5.5 W/(m²K). The convective heat transfer then varies between 0.5 and 5.5 W/(m²K), depending on the surface type and on operation mode. This shows that the radiant heat transfer varies between 50% and 90% of the total heat transfer [11].

Radiant panel heating is characterised by the fact that heating is associated with a yielding of heat with low temperature because of physiological reasons. Thus, at the radiant floor panels, the temperature must not exceed +29 °C, and at the radiant ceiling panels, the temperature will not exceed 35-40 °C, depending on the position of the occupier (in feet) and the occupier distance to the panels, in accordance with thermal comfort criteria established by ISO Standard 7730 [12]. A vertical air temperature difference between head and feet of less than 3 °C is recommended. In a well-insulated building, the selected floor surface material is of crucial importance in regard to how warm the floor feels. For example, oak parquet at a temperature of 21 °C and stone floor at a temperature of 26 °C feel neutral and roughly the same under a bare foot according ISO/TS 13732-2 [13]. However, this is not always the case, the percent dissatisfied (PD) in % has a relation with floor surface temperature as follow [14]:

$$\text{PD} = 100 - 94 \exp\left(-1.387 + 0.118 t_f - 0.0025 t_f^2\right)$$  \hspace{1cm} (1)

where $t_f$ is the floor surface temperature.

The vertical profile of the air temperature for two types of radiant heating panels is illustrated in figure 2. The radiant part is lower (70%) at the floor heating than the ceiling in terms of heating (85%) because thermal convection is developed more in the case of floor heating panels [15].

![Figure 2. Temperature profile for low-temperature radiant heating](image)

The higher mean radiant temperature in radiantly heated space means that the air temperature can be kept lower than in convectively heated space. This has the advantage that the relative humidity in winter may be a little higher.

The heat transfer between the water and surface is different for each system configuration. Therefore, the estimation of heating capacity of systems is very important for the proper system design. Two calculation methods included in ISO 11855 are simplified calculation methods depending on the type of system, and finite element method or finite difference method.

The simplified calculation methods are specific for the given system types within boundary conditions. Based on the calculated average surface temperature at given distribution fluid temperature and operative temperature in the space, it is possible to determine the steady state heating capacity. Thus, the heating capacity of the floor, wall and ceiling heating systems is [16]:

- floor heating and ceiling cooling: \[ q = 8.92 (t_a - t_{s,m})^{1.1} \]  \hspace{1cm} (2)
- wall heating and wall cooling: \[ q = 8.0 (t_a - t_{s,m}) \]  \hspace{1cm} (3)
- ceiling heating: \[ q = 6.0 (t_a - t_{s,m}) \]  \hspace{1cm} (4)
where: $q$ is the heating capacity, in W/m$^2$; $t_o$ is the operative (comfort) temperature in the space, in °C; $t_{s,m}$ is the average surface temperature, in °C.

The heating capacity for floor and ceiling is up to 100 W/m$^2$ and 40 W/m$^2$, respectively. To maintain a stable thermal environment, the control system needs to maintain the balance between the heat gain of the building and the supplied energy from the system.

3. Comparative analysis of radiant panel system performance

An investigated residential building located in Timisoara, Romania, is shown in figure 3. The investigated building and its heating systems are modelled using TRNSYS software.

![Figure 3. Residential building](image)

Living room (LR); hallway (HW); bathroom (BTR); bedrooms (BR1, BR2, and BR3)

3.1. Description of panel systems

The panel heaters may be the floor heating panels, wall heating panels, ceiling heating panels, and floor-ceiling heating panels. The floor heating panels have a total surface area of 160 m$^2$. The wall heating panel is located at the exterior wall and has a total surface area of 177 m$^2$. The ceiling heating panel is located at the ceiling of the first and second storey of the house and has total surface area of 160 m$^2$. The floor-ceiling heating panel operates as a ceiling heating of the lower story and as a floor heating of the upper story. Its total surface area is 80 m$^2$.

The main component of the heating panels is the pipe where the hot water flows. The hot water inlet temperature has the same value of 37 °C for all heating systems. For all heating panels, classic boilers were used to generate heat by using natural gas. The water circulation pump uses electricity to operate.

Four water-based radiant systems are analysed: (1) floor heating, (2) wall panel heating, (3) ceiling heating, and (4) floor-ceiling heating.

3.2. Primary energy consumption of heating system

The primary energy consumption $E$ per heating season of the analysed building is calculated by using the following equation:

$$E = E_g + \frac{E_{el}}{\eta_{el}}$$

(5)

where $E_g$ is the consumption of natural gas per heating season; $E_{el}$ is the consumption of electrical energy per heating season; $\eta_{el}=0.4$ is the electricity generation efficiency, defined as ratio between finally produced electric energy and the primary energy consumption for electricity generation. If the boilers utilise solar energy, then a significant primary energy saving is possible.
3.3. Operating cost
Total operating cost \( C_T \) to run the heating system is calculated by using the following equation:

\[
C_T = c_{el}E_{el} + k c_{g}E_{g}
\]  
(6)

where \( c_{el} \) is the specific cost of electricity; \( c_{g} \) is the specific cost of natural gas with energy value of 33,338 kJ/m³; \( k \) is the correction coefficient of the natural gas consumption. The specific conditions of Romania can be considered: \( c_{el}=0.11 \) €/kWh, \( c_{g}=0.29 \) €/m³, and \( k=1.05 \) [17].

3.4. Carbon dioxide (CO₂) emission
The CO₂ emission of the heating system during its operation is calculated with following equation:

\[
CO_2 = g_{g}E_{g} + g_{el}E_{el}
\]  
(7)

where \( g_{g} \) is the specific CO₂ emission factor for natural gas, and \( g_{el} \) is the specific CO₂ emission factor for electricity (Table 1) [18].

| Type of fuel   | Emission factor (kg CO₂/kWh) |
|---------------|-----------------------------|
| Electric energy| 0.547                       |
| Natural gas   | 0.205                       |

3.5. Results and discussion
In these investigations, the four analysed panel systems are simulated by using TRNSYS software during their operation at the heating season. For each of the four analysed panel systems, the energy consumption, the operating cost of building heating, the CO₂ emission due to the building heating, and temperatures of rooms were calculated.

The primary energy consumption during the heating season is illustrated in figure 4. The system with the floor-ceiling heating panel has the lowest energy consumption (7005 kWh/year) and the system with the ceiling heating panel has the highest energy consumption (9630 kWh/year). Their difference is approximately 27.2%. The system with a floor-ceiling heating panel has a 10% lower energy consumption lower than that of the system with the wall heating panel and 22% lower than that of a system with the floor heating panel.

![Figure 4. Energy consumption of heating systems](image)

![Figure 5. Nominal power of boiler](image)

Figure 5 shows the value of the boiler nominal power for all four systems. The minimum nominal power of the boiler is required for system with the floor-ceiling heating panel (8.5 kW), and the highest is required for the system with the ceiling heating panel (13.7 kW). The nominal power outputs of the other two systems are similar to that of system with the ceiling heating panel.
In figure 6, the operation cost of heating is shown. These data indicate that the largest heating cost is for the heating system with a ceiling-heating panel (500 €), and the lowest cost is for the heating system with the floor heating panel (380 €). The use of the system with the floor heating panel instead of a system with the ceiling heating panel would yield a total financial savings of 120 € per heating season.

As seen in figure 7, the CO₂ emission of the heating systems calculated for February, month with lowest winter temperatures, is the lowest for the system with the floor-ceiling heating panel (1400 kg CO₂) and the highest for the system with the ceiling heating panel (1834 kg CO₂), a difference of 23.7%.

In terms of checking proper operation of all four systems, figure 8 illustrates the mean operative indoor air temperature of rooms and the desired temperature of rooms in February. It is found that for all heating systems, the mean indoor air temperatures do not significantly deviate from the set-point operative temperature. The largest deviation (approximately 1 °C) is found with the floor-ceiling panel system in room BR3 on the first storey of building, such that the mean temperature in this room is 19.1 °C instead of the desired 20 °C.

4. Conclusions
This study showed that the floor-ceiling heating system has the best performance in terms of the lowest energy consumption, operation cost, CO₂ emission, and the nominal boiler power. In addition, it is important to note that the next best performing radiant system is the system with the wall heating panel. The classical ceiling heating system displays the worst performances in terms of the listed parameters.

The comparison of the room operative air temperatures and the set-point operative air temperature indicates that all radiant panel systems provide satisfactory results without significant deviations.

New investigations should be performed to examine other low-temperature heating systems and their combinations to be integrated in solar systems.
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