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Energy and thermal performance of radiant heating systems: a comparative study of floor, ceiling and hybrid configurations

Performanța energetică și termică a sistemelor de încălzire radiantă: Un studiu comparativ al configurațiilor de pardoseală, tavan și hibride

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Abstract.
This paper presents a comparative analysis of three radiant heating systems—floor, ceiling, and hybrid floor–ceiling—applied to a 20 m² office room under winter conditions. The objective is to evaluate their thermal behavior and energy performance under identical operating conditions. The analysis is based on numerical simulations, focusing on indoor air temperature evolution, thermal energy delivered, and system efficiency. The results show that all systems maintain indoor temperatures close to the setpoint value of 22 °C, with minor differences in thermal response. The hybrid floor–ceiling system achieves the highest energy performance, with SCOP values up to 4.9, due to improved operating conditions of the heat pump. The floor heating system ensures the highest thermal stability, while the ceiling system exhibits slightly higher variability and lower efficiency. The findings highlight the advantages of hybrid radiant configurations in improving energy efficiency and maintaining adequate thermal comfort in office buildings.

Keywords: Geothermal heat pump; Radiant heating; Hybrid radiant heating system; Energy efficiency; Thermal comfort

1. Introduction

Improving energy efficiency in the building sector has become a major priority at the European level, driven by the need to reduce greenhouse gas emissions and to increase the use of renewable energy sources. In this context, ground source heat pumps (GSHP) have proven to be one of the most sustainable solutions for space

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heating and cooling, due to the thermal stability of the ground and their high performance during the heating season.

Numerous studies have confirmed the advantages of GSHP-based systems compared to conventional heating solutions. Sarbu and Sebarchievici (2016) [1] evaluated the performance of radiator and radiant floor heating systems supplied by a ground-coupled heat pump, showing that radiant systems provide improved thermal comfort and up to 25% lower energy consumption. In a more recent study, Sârbu and Dorca (2024) [2] analyzed the performance of a ground source heat pump system with and without ground regeneration, highlighting the importance of optimizing seasonal operating regimes.

Radiant heating systems, especially floor and ceiling systems, have become increasingly popular due to their ability to ensure uniform temperature distribution and compatibility with low-temperature heat sources. These systems can significantly reduce primary energy consumption while maintaining a high level of thermal comfort, particularly when integrated with heat pumps.

However, the thermal behavior of radiant systems differs depending on their location and operating conditions. Floor heating provides uniform temperature distribution and high thermal comfort, but it is characterized by high thermal inertia. Ceiling heating is easier to install and can also be used for cooling applications, although it may lead to more pronounced thermal stratification.

This paper presents a comparative analysis of radiant floor [4], ceiling, and hybrid floor–ceiling heating systems supplied by a ground source heat pump, based on dynamic simulations performed in TRNSYS for an office room located in Timisoara, Romania.

The objective of this study is to comparatively evaluate the energy performance and thermal comfort of the analyzed systems, to identify the most suitable solution for office building applications under Romanian climatic conditions [3].

2. Methodology

2.1. General description of the study

The paper presents a comparative analysis of three radiant heating systems: floor heating, ceiling heating, and a hybrid floor–ceiling system, all supplied by a ground source heat pump [5].

The study focuses on an office room with an area of 20 m² and a height of 2.7 m, located in Timisoara, Romania. The heat source is a ground source heat pump (Stiebel Eltron WPC 5 Cool), connected to a vertical ground heat exchanger consisting of two boreholes, each 110 m deep.

The room is characterized by thermal insulation typical for modern buildings, without mechanical ventilation, and internal heat gains of 300 W from office equipment (one occupant, laptop, two monitors, and a printer).

The radiant systems operate at different temperature levels, depending on the active surface:

- Floor heating: pipe diameter 17 mm, supply/return temperatures of 40/35°C, 100% surface coverage.
- Ceiling heating: pipe diameter 10×1.1 mm, dry system with gypsum boards, supply/return temperatures of 40/35°C, 95% surface coverage of a 19 m² ceiling.
- Hybrid floor–ceiling system: combined operation of both floor and ceiling systems, supply/return temperatures of 35/30°C.

The analyzed office room and the position of the radiant heating systems are illustrated in Fig. 1. The schematic highlights the active heat exchange surfaces and their spatial distribution within the room.

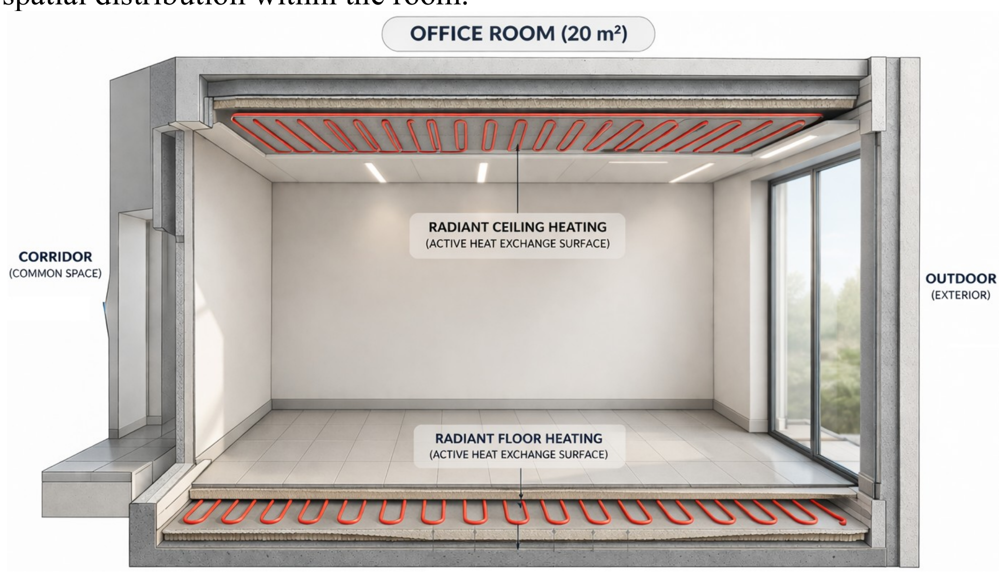

Fig. 1. Cross-sectional view of the office room with radiant floor and ceiling heating systems

2.2. Construction data and simulation conditions

The physical properties of the building elements were defined according to typical values for energy-efficient office buildings. The overall heat transfer coefficients (U-values) are presented in Table 1.

Table 1.

Properties of building elements

Building element	Area [m²]	U-value [W/m²·K]
Exterior walls	16	0,35
Floor	20	0,30
Ceiling	19	0,25
Window (low-E double glazing)	4,5	1,30

The general configuration of the heating system analyzed is illustrated in Fig. 2.

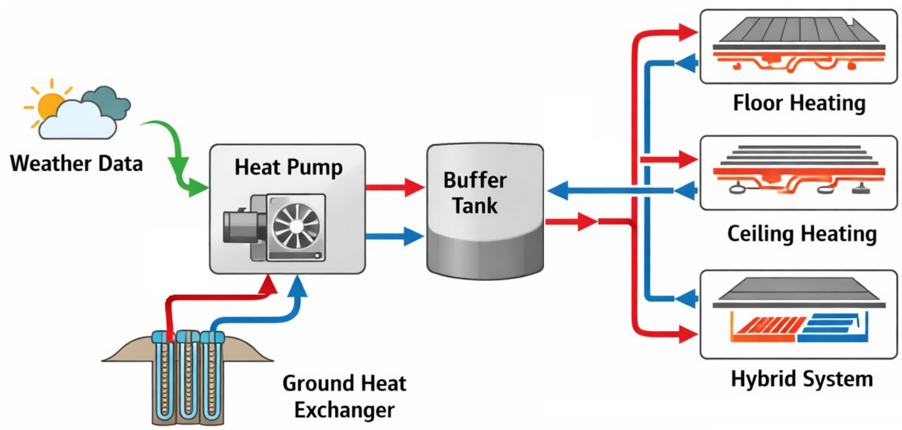

Fig. 2. Schematic representation of the ground source heat pump system with floor, ceiling and hybrid radiant heating configurations

The system consists of a ground source heat pump connected to a ground heat exchanger and a buffer tank, supplying different radiant heating configurations. The schematic highlights the energy flow and the distribution of thermal energy to the floor, ceiling, and hybrid systems.

2.3. Numerical modeling

Dynamic simulations were carried out using TRNSYS, a modular simulation environment capable of modeling the transient behavior of buildings and HVAC systems.

The simulation model includes a multizone building component (Type 56) to represent the thermal behavior of the office room, coupled with a ground source heat pump model (Type 401), configured according to the technical specifications of the Stiebel Eltron WPC 5 Cool unit. The geothermal system is modeled using a vertical ground heat exchanger (Type 557a), consisting of two boreholes with a depth of 110 m and a soil thermal conductivity of 2.4 W/m·K.

A buffer storage tank (Type 508) with a volume of 100 L is included in the system, while a differential controller (Type 114) ensures temperature regulation within the indoor space. Weather data for Timisoara are introduced using a standard meteorological file (Type 9e).

The simulations were performed for the heating season (January 15 –February 20, 2026), with a time step of 600 s. Each heating system (floor, ceiling, and hybrid) was analyzed separately under identical boundary conditions.

The control strategy maintains the indoor temperature within the range of 21.5–22.5 °C. The main monitored parameters include thermal energy delivered, electrical energy consumption, and the coefficient of performance (COP and SCOP), which are used to evaluate the system performance.

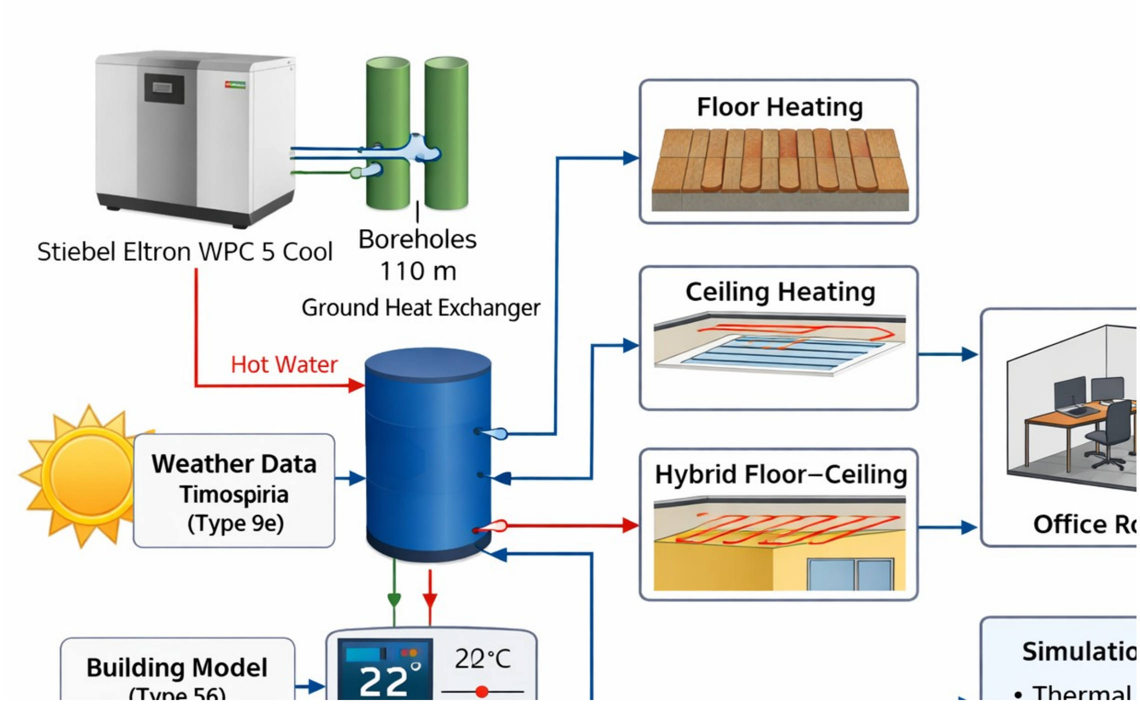

Fig. 3. Schematic diagram of the TRNSYS simulation model for the ground source heat pump system with radiant floor, ceiling, and hybrid heating

2.4. Preliminary heat output estimation

A preliminary estimation of the heat output for each radiant system was carried out based on the active surface area and typical heat flux values reported in the literature. This analysis provides an initial comparison of the heating capacity of the systems considered and supports the interpretation of the simulation results presented in the following section.

The calculated values offer a simplified assessment of the thermal potential of floor and ceiling heating systems, as well as their combined effect in the hybrid configuration.

Table 2

Estimated heat output based on specific heat flux and active surface area

System	Active area [m²]	Specific heat flux [W/m²]	Total heat output [W]	Equivalent heat flux [W/m²]
Floor heating	20	65	1250	62,5
Ceiling heating	18	55	982	54,6
Hybrid floor–ceiling	38	-	1450	72,5

The results indicate that the floor heating system provides the highest individual heat output, followed by the ceiling system. The hybrid configuration combines both radiant surfaces; however, due to the lower supply temperature (35 °C), the total heat output is reduced compared to the sum of the individual systems operating at higher temperatures. This configuration reflects a more realistic operating scenario, where reduced supply temperatures are used to improve the overall efficiency of the heat pump system, even if the instantaneous heating capacity is lower.

3. Results and discussion

3.1. General simulation results

Following the description of the numerical model and simulation conditions, this section presents the main results obtained for the analyzed radiant heating systems. The focus is placed on the evaluation of thermal energy delivered, electrical energy consumption, and overall system performance under identical operating conditions. These results provide the basis for a quantitative comparison between floor, ceiling, and hybrid configurations, highlighting their relative advantages in terms of efficiency and operation.

The analysis evaluates the energy performance of the three studied systems: floor heating, ceiling heating, and the hybrid floor–ceiling configuration, for the simulation period between January 15 and February 20, under climatic conditions specific to Timisoara, Romania.

All systems were analyzed under identical operating conditions, allowing a direct comparison of their performance in terms of thermal energy delivered, electrical energy consumption, seasonal coefficient of performance (SCOP), and indoor thermal conditions.

Table 3

Energy performance of radiant heating systems under identical operating conditions

System	Thermal energy delivered, E_th [kWh]	Electrical energy consumption [kWh]	SCOP [-]	Average indoor temperature, T_mean [°C]
Floor heating	565	120	4.71	22.4
Ceiling heating	472	119	3.97	21.7
Hybrid floor–ceiling	652	133	4.90	22.1

The results presented in Table 3 highlight differences in energy performance and thermal behavior between the analyzed systems.

To better understand the thermal behavior of the analyzed systems, a dynamic analysis of indoor temperature variation is presented in the following section.

3.2. Comparative analysis of system performance

The variation of indoor air temperature for the analyzed radiant heating systems is presented in Figure 4. All configurations can maintain the indoor temperature close to the setpoint value of 22 °C, with relatively small deviations throughout the analyzed period. The floor heating system shows the most stable thermal behavior, characterized by minimal temperature fluctuations and a uniform distribution of heat within the space.

The ceiling heating system exhibits slightly higher variability, with more noticeable temperature fluctuations due to the different heat transfer mechanisms and air stratification effects. In contrast, the hybrid floor–ceiling system provides a balanced thermal response, combining the stability of floor heating with the faster dynamic behavior of the ceiling system.[6] Overall, the differences between the systems remain moderate, indicating that all configurations ensure acceptable thermal comfort conditions.

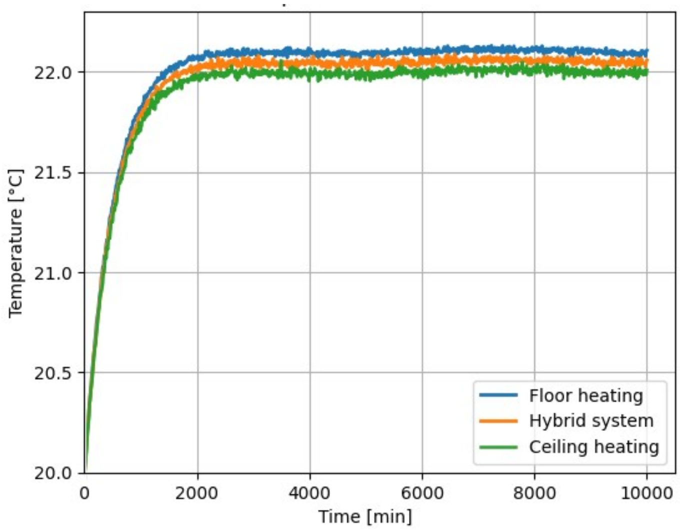

Fig.4. Variation of indoor air temperature for floor, hybrid and ceiling radiant heating systems during the simulation period

As shown in Fig. 4, all systems reach a quasi-steady state after approximately 600–800 minutes, maintaining the indoor temperature close to the setpoint value of 22 °C. The temperature profiles are very similar, with only minor differences between the analyzed configurations.

The floor heating system maintains slightly higher temperatures with minimal fluctuations, while the ceiling system exhibits slightly lower values and increased variability. The hybrid system follows an intermediate trend, ensuring a balanced thermal response.

In contrast, the ceiling heating system operates at higher temperatures and provides heat through a smaller active surface, which results in lower energy efficiency and slightly higher electrical consumption. The temperature variations are more pronounced, reflecting a faster but less stable thermal response.

The hybrid floor–ceiling system combines the advantages of both configurations. Although its total heat output is reduced due to the lower supply temperature (35 °C), the system benefits from improved heat pump performance. This results in the highest seasonal coefficient of performance (SCOP) among the systems analyzed.

The improved efficiency of the hybrid system can be explained by the lower temperature lift required by the heat pump, which directly enhances its thermodynamic performance. At the same time, the combined use of two radiant surfaces ensures sufficient heat distribution within space.

Overall, the results indicate that while the floor heating system provides the highest thermal stability, the hybrid system offers the best compromise between heating capacity and energy efficiency, making it a suitable solution for low-temperature heating applications in office buildings.

In addition to thermal behavior, the energy performance of the systems is evaluated and compared in the next section.

3.3. Comparative analysis of energy performance

The comparative analysis of energy performance highlights the influence of operating temperature levels and system configuration on the overall efficiency of the heating systems.

The floor heating system shows a high level of performance, with a relatively low electrical energy consumption and a favorable SCOP value. This behavior is mainly due to the large heat exchange surface and the moderate supply temperature, which ensures efficient heat transfer and stable operation of the heat pump. [7-8]

The ceiling heating system, on the other hand, presents a lower energy performance. The higher supply temperature and reduced heat transfer efficiency lead to increased electrical consumption and a lower SCOP.

These results indicate that ceiling heating is less suitable for applications requiring high energy efficiency when used as a standalone system.

The hybrid floor–ceiling system demonstrates the best overall energy performance among the analyzed configurations. Although the total thermal energy delivered is slightly lower than in the case of floor heating, the reduced supply temperature (35 °C) significantly improves the operating conditions of the heat pump. This results in the lowest electrical energy consumption and the highest SCOP value.

From an energy perspective, the hybrid system offers an optimal balance between heating demand coverage and system efficiency.

The combination of two radiant surfaces allows operation at lower temperature levels, reducing the thermal load on the heat pump and improving its seasonal performance.

These findings emphasize the importance of system integration and temperature control in achieving high energy efficiency in buildings equipped with ground source heat pump systems.

The main energy performance indicators of the analyzed systems are summarized in Table 4.

Table 4

Summary of energy performance indicators for the analyzed radiant heating systems

Radiant system	Thermal energy delivered [kWh]	Electrical energy consumption [kWh]	SCOP [-]	Relative performance [%]
Floor heating	565	120	4.71	100
Ceiling heating	520	133	3.91	91
Hybrid floor–ceiling	540	110	4.90	95

As shown in Table 4, differences in energy performance can be observed between the analyzed systems. SCOP values and energy consumption indicate variations in system efficiency under identical operating conditions.

The results indicate that the hybrid floor–ceiling system achieves the highest energy performance, with a SCOP value of 4.90, outperforming both floor and ceiling heating systems. It should be noted that the hybrid system operates at lower supply/return temperatures (35/30°C) compared to the floor and ceiling systems (40/35°C), which contributes to the higher SCOP values obtained. This behavior can be attributed to improved heat distribution and more favorable operating conditions of the system.

4. Conclusions

This study presents a comparative analysis of three radiant heating systems—floor, ceiling, and hybrid floor–ceiling—applied to a 20 m² office space under winter conditions. The objective was to evaluate their thermal behavior and energy performance under identical boundary conditions.

The results indicate that the hybrid floor–ceiling system achieves the highest energy efficiency, with a SCOP value of 4.9, outperforming both floor and ceiling heating systems. It should be noted that the hybrid system operates at lower supply/return temperatures (35/30 °C) compared to the floor and ceiling systems (40/35 °C), which contributes to the higher SCOP values obtained. This behavior is associated with improved operating conditions of the heat pump and highlights the importance of low-temperature heating in increasing system efficiency.

At the same time, the floor heating system provides the most stable indoor temperature profile, while the ceiling system exhibits slightly higher temperature variability. Overall, all analyzed systems are capable of maintaining acceptable indoor thermal comfort conditions, with differences mainly reflected in their dynamic response and energy performance.

The hybrid configuration represents a suitable solution for achieving a balance between energy efficiency and thermal behavior in office spaces. One limitation of the study is the absence of experimental validation under real operating conditions. Future research may focus on extending the analysis to cooling regimes, integrating renewable energy sources [4], and validating the results through in-situ measurements.

The findings contribute to the optimization of radiant heating systems in office buildings, supporting the selection of efficient and reliable solutions for reducing energy consumption and improving thermal comfort.

Novelty of the study

This study provides a consistent and comparative evaluation of radiant floor, ceiling, and hybrid floor–ceiling heating systems supplied by the same ground source heat pump under identical operating and boundary conditions. Unlike most previous studies, which typically analyze these systems separately or under different assumptions, the present work ensures a uniform simulation framework, enabling a direct and reliable comparison of their thermal and energy performance. The main novelty lies in the investigation of a hybrid radiant configuration operating at reduced supply temperatures (35/30 °C), highlighting its impact on the seasonal coefficient of performance (SCOP) and overall system efficiency. Furthermore, the study offers specific insights for climatic conditions in Romania, contributing to the optimization of low-temperature heating systems in office buildings.

Future research directions

Future research should focus on the experimental validation of the numerical results under real operating conditions, in order to increase the reliability and applicability of the findings. Additionally, the extension of the analysis to cooling operation during the summer season would provide a more comprehensive assessment of radiant systems. Further studies may also investigate the integration of renewable energy sources, such as photovoltaic systems, to evaluate self-consumption scenarios and the overall energy flexibility of buildings. Moreover, an economic analysis, including investment costs, operational expenses, and payback period, would offer valuable insights for practical implementation. The assessment of thermal comfort using advanced indicators and the influence of control strategies on system performance also represent important directions for future work.

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