Adjusting the design of a radiant heating system for office retrofit

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Abstract. Installation of low-exergy water-based radiant systems can help alleviate the negative effects of increased energy consumption due to their suitability for combination with low-grade renewable energy sources. Radiant heating and cooling installations in buildings are common, but their application in existing buildings as part of retrofit is relatively rare. The present study investigated some of the aspects of the installation of radiant heating systems in existing buildings. Wall and ceiling systems with pipe underneath the surface were considered because of various potential benefits. These include the possibility of operating as cooling in summer and heating in winter, easy installation in existing buildings, minor space requirements, and no or little need to reduce the height of the storey, especially in the case of walls. It was found that with a thermally conductive core, only a thin insulation layer of 1 cm may suffice if the temperature difference between rooms is relatively small. For an insulating core, no insulation may be needed even at higher temperature differences between rooms. Reducing the pipe spacing to about 5 cm was found to be efficient in terms of increased thermal output per 1 cm of spacing. The location of the insulation had a small effect on the thermal losses, but the output was higher for insulation placed on the outer side of the wall due to a more uniform temperature distribution in the structure. This configuration also allows for considerably higher heat storage capacity.

Keywords. Radiant heating, retrofit, thermal performance, ceiling heating, wall heating.
DOI: https://doi.org/10.34641/clima.2022.205

1. Introduction

Radiant heating and cooling are commonly used in newly constructed buildings in situations where they can provide benefits compared to convective systems such as fan coils, radiators, air terminals and beams [1, 2, 3, 4]. The benefits of radiant systems involve the suitability for combination with renewable energy sources due to the water temperature close to room temperature [5, 6, 7, 8], comfortable thermal environment [9, 10, 11] and use of thermal mass for peak load shifting [12, 13, 14]. These favorable characteristics could make radiant systems a suitable heating and cooling solution for building retrofitting. To achieve this, the construction of the radiant systems needs to be adapted to the retrofitted room, minimize negative impacts such as reduction of the room height or a need for destruction of existing structures, while providing the desired thermal behavior.

In building retrofitting, placing pipes directly on the existing ceiling or wall structure can be practical because it is easy to do and leads to a relatively high thermal output and low thermal losses [15]. Its thermal characteristics depend on the conductivity of the thermal core and the spacing of the pipe. Using an insulating thermal core results in a fast thermal response, whereas a conductive core slows the thermal response but provides a potential for thermal storage [16, 17].

This study aims to provide conceptual recommendations on the construction of radiant heating and cooling systems in existing rooms. Two radiant systems that are potentially suitable for building retrofitting were selected. These systems are ceiling with pipes attached to the bearing structure (**Fig. 1**) and pipes attached to an existing wall (**Fig. 2**). The systems were studied in the heating operation mode, but the results are also applicable to cooling conditions, provided that the temperature difference between water and room temperature is similar to that in heating cases. The parameters considered in this study included the placement of thermal insulation on the inner/outer surface of the thermal core, pipe spacing, wall thickness, and thermal conductivity of the core. The effect of these parameters on the thermal output and losses and on the homogeneity of the surface temperature was studied. To accomplish this, a simulation model was created in a verified software tool. The results are recommendations for the design of radiant heating systems that can be applied to existing buildings.

2. Description of the radiant systems and boundary conditions

Only radiant heating and cooling systems with pipes underneath the inner surface were considered. The two selected radiant systems comprise a radiant ceiling with pipes attached to the supporting structure (**Fig. 1**) and pipes attached to an existing wall (**Fig. 2**). Such systems are efficient in terms of heat transfer between the pipe and the room and should be able to provide reasonable variability of design solutions and thermal behaviors. Both systems are well suited both for heating and cooling operation, meaning that they can be operated all year round, provided that they are connected to a corresponding energy source, e.g. a heat pump. The thermal conductivity of the material layers is shown in **Tab. 1**. In the analysis, the thermophysical properties of the materials were considered isotropic, temperature independent and constant in time.

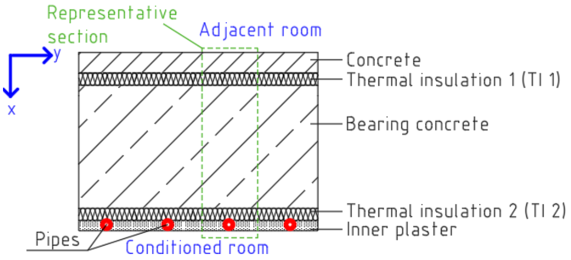

Fig. 1 – Radiant ceiling.

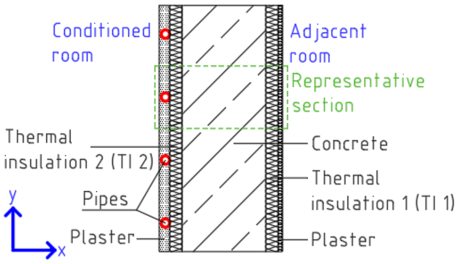

Fig. 2 – Radiant wall.

Representative sections of the radiant systems were used for the calculation. The room temperature (T_i) was 20°C. The mean water temperature was 35°C, which is representative of relatively demanding winter climatic conditions in Central Europe to cover a critical situation. For the wall system, this water temperature ensures that the surface temperature is well below the maximum limit for wall systems of approximately 40°C. For the ceiling system, the water temperature is relatively high, and depending on the resulting surface temperature and room geometry, it could lead to a risk of discomfort due to radiant temperature asymmetry. Therefore, in practical situations, care must be taken to verify if the comfort limits are met and adjust the water temperature as needed.

The temperature difference between the conditioned room and the adjacent room (T_i - $T_{i,adj}$) was 5 K, except for the case of C-3 and W-3, where the temperature difference (T_i - $T_{i,adj}$) was 15 K. The 5 K represented a conditioned adjacent room. This temperature difference may seem small, but it was the relative difference between the cases and the loss in W/m² per 1 K temperature difference that was most relevant for the analysis. The 15 K represented an unheated adjacent room. The total heat transfer coefficient on the thermo-active surface was 6.5 W/(m².K) for the ceiling system and 8 W/(m².K) for the wall system. The heat transfer coefficient on adjacent surfaces that were not thermally active was 6 W/(m².K). The heat transfer coefficient between the pipe and water was determined to be 1274 W/(m².K). This value is realistic, and further increasing or decreasing this value by several hundreds of W/(m².K) has negligible effect on the results [17].

Tab. 1 - Thermophysical properties of materials.

Material	Thermal conductivity λ (W/(m·K))	Thickness d (m)
1 – Simple concrete	0.6	0.05
2 – Reinforced concrete (RC)	1.58	0.2 (wall) or 0.3 (ceiling)
3 – Aerated concrete (AC)	0.15	
4 – Thermal insulation	0.035	0.01
5 – Pipe PE-Xa*	0.35	-
6 – Inner plaster	0.49	0.025

* outer diameter 10.1 mm, wall thickness 1.1 mm

The two systems were considered to be located in a corner room with two partition walls dividing the conditioned room from adjacent rooms (**Fig. 3**). In the present study, the room was designated as an office room, but the results are also applicable to other room types with similar boundary conditions. Another adjacent room was located above the conditioned room. This means that in the present study, the ceiling or walls that contained pipes were not exposed to weather conditions.

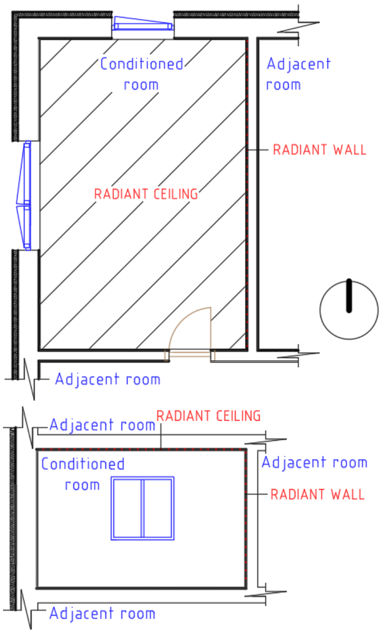

Fig. 3 – Location of office room and radiant systems.

3. Principle of heat transfer calculation

The numerical model was created and solved using CalA software [18] developed to calculate two-dimensional heat transfer in building structures. The software was verified following the procedure in ISO 11855 [19], Part 2 (Annex D). The verification can be found in the supplementary material to Ref. [16]. The governing equation described the problem as two-dimensional transient heat conduction as follows:

$$\frac{\partial T}{\partial \tau} = \alpha\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \tag{1}$$

where T, τ and α represent the temperature (K), time (s) and thermal diffusivity (m^2/s), respectively. Thermal diffusivity is the ratio of the thermal conductivity of a substance to the product of its density and its specific heat capacity. The boundary conditions defining the specific heat flux on the surface of a computational domain were calculated according to Newton's law of cooling, assuming adiabatic wall boundaries. The boundary condition on the surface of the computational domain was:

$$-\lambda\left(\frac{\partial T}{\partial n}\right)_w = h\left(T_w - T_f\right) \tag{2}$$

where h is the total heat transfer coefficient (convective and radiative) between the radiant surface and the environment ($W/(m^2.K)$); T_w is the temperature of wall surface (K), T_f is the temperature of the surrounding fluid (K), n is index denoting a line perpendicular to the surface.

The boundary condition on the adiabatic wall boundary was as follows:

$$-\lambda\left(\frac{\partial T}{\partial n}\right)_w = 0 \tag{3}$$

In **Eq. 2**, w denotes the surface of the computational domain through which heat transfer occurs between the wall or ceiling structure and the rooms. In **Eq. 3**, w denotes the adiabatic boundary between two wall sections along the horizontal (wall) or vertical (ceiling) symmetry plane. The calculation was converged when the sum of the normalized heat flux residues met the convergence criterion:

$$\frac{\sum_{i=1}^{k} q_{,i}}{\sum_{i=1}^{k} |q_{,i}|} \leq 10^{-6} \tag{4}$$

where q_i is the heat flux entering and leaving the control volume.

4. Cases studied

The ceiling system (C) can be easily constructed by adding a thermally active layer to the bearing structure (**Fig. 1**). The default thickness of the bearing structure and the spacing of the pipes used in the calculations were 30 and 10 cm, respectively. The construction factors considered that can affect the thermal performance of the ceiling were the presence of thermal insulation in the floor of an adjacent room, the presence of insulation between the thermoactive layer and the thermal core, and the thermal conductivity of the bearing concrete (reinforced concrete - RC, aerated concrete - AC). The five cases of ceilings in **Tab. 2** were planned to study the effect of these factors. The parameter of interest in each case is written in bold in the table. The cases that are compared together are explained as follows:

- C-1 and C-2 – effect of the presence of original insulation in the floor of an unheated adjacent room on thermal losses to the room,
- C-1 and C-4 – effect of thermal conductivity of the concrete core in case of no thermal insulation,
- C-3 and C-4 – effect of thermal conductivity of the concrete core and low temperature in the adjacent room in case of no thermal insulation (T_i - $T_{i,\,adj}$) is 15 K,
- C-1 and C-5 – effect of adding insulation layer between the thermoactive layer and the thermal core.

A wall system (W) with pipes in plaster can be built by embedding the pipes in a newly created plaster attached to an existing wall (**Fig. 2**). The default thermal core thickness was 20 cm as compared to the 30 cm used for the ceiling. The default pipe spacing was 10 cm. The design factors considered that can affect the thermal performance were the conductivity of the thermal core (reinforced concrete - RC or aerated concrete - AC), pipe spacing, and the presence of insulation between the thermoactive layer and the core. The seven cases of walls studied are listed in **Tab. 2**, where the parameters of interest are written in bold. The cases are compared with each other as follows:

- W-1 and W-2 – effect of adding insulation layer on the outer side of the concrete core.

- W-1 and W-4 – effect of thermal conductivity of the concrete core in case of no thermal insulation,
- W-3 and W-4 – effect of thermal conductivity of the concrete core and low temperature in the adjacent room in case of no thermal insulation (T_i - $T_{i,\,adj}$) is 15 K,
- W-1 and W-5 – effect of adding insulation layer between the thermoactive layer and the thermal core,
- W-5, W-6 and W7 – effect of pipe spacing.

The insulation thickness on the outer side (TI 1) and inner side (TI 2) of the concrete core in **Tab. 2** is defined in **Fig. 1** and **Fig 2**.

Tab. 2 - Cases studied.

Case	TI 1	TI 2	Pipe spacing (cm)	Core material
CEILING SYSTEM:				
C-1	no	no	10	RC
C-2	**yes**	no	10	RC
C-3*	no	no	10	**AC**
C-4	no	no	10	**AC**
C-5	no	**yes**	10	RC
WALL SYSTEM:				
W-1	no	no	10	RC
W-2	**yes**	no	10	RC
W-3*	no	no	10	**AC**
W-4	no	no	10	**AC**
W-5	no	**yes**	10	RC
W-6	no	yes	**5**	RC
W-7	no	yes	**15**	RC

*(T_i - $T_{i,adj}$) *= 15 K instead of 5 K*

5. Results and discussion

The results for the representative sections of the radiant heating systems are shown in **Figs. 4** to **10**. **Figs. 4, 5,** and **6** illustrate the temperature distribution in the structure for selected cases. The thermal output (q_i) and losses (q_e) are shown in **Fig. 7** for the ceiling and **Fig. 8** for the wall. All heat flux values presented refer to square meter of wall (ceiling) surface area. The average temperature ($T_{suf,i}$) and the difference between the maximum and minimum surface temperature ($T_{surf,max}$ - $T_{surf,min}$) are shown in **Fig. 9** for the ceiling and **Fig. 10** for the wall.

Comparing C-1 and C-2 where in the case of C-2 the original insulating layer was preserved in the floor showed that the presence of just 1 cm insulation reduced the heat loss by 37% (**Fig. 7**). The losses were similar when insulation was placed on the inner side of the ceiling between the thermo-active plaster and the concrete core (C-1 vs. C-5). However, the output and storage capacity were different depending on the location of the insulation. In C-2 (insulation on the outer side), the output was 10% higher compared to C-5 (insulation on inner side) due to the more homogeneous surface temperature distribution, as illustrated in **Fig. 4**. Besides, in C-5 the thermal storage capacity is very low compared to C-2, resulting in a very fast thermal response. The same principles were valid for the wall system (**Fig. 8**), but the effect of adding thermal insulation was even more important because of the lower thickness of the concrete core. Additional calculations showed that adding insulation up to about 3 cm was sensible. A further increase in insulation thickness reduced the losses, but the reduction per 1 cm of insulation became relatively small.

A comparison of C-1 and C-4 illustrates the effect of the thermal conductivity of the concrete core if there is no thermal insulation. The effect is tremendous. Thermal losses were lower by 80% when the concrete core was made of a thermally insulating material (AC) compared to conductive concrete (RC), assuming no additional thermal insulation (**Fig. 7**). Increasing the temperature difference (C-3) led to a higher overall heat loss, but a lower specific loss per 1 K of the temperature difference between the heated and the adjacent room. This means that little or no insulation needs to be added to prevent losses if the concrete core is made of an insulating material. This point is also illustrated by comparing the wall systems W-4 and W-5 (**Figs. 5 and 8**). The use of an insulating concrete core (W-4) reduced losses by 57% compared to a conductive core with 1 cm of thermal insulation (W-5). Moreover, with the insulating core the output was 8% higher while also providing a certain potential for thermal storage.

A comparison of thermal output for pipe spacing of 5 cm (W-6), 10 cm (W-5) and 15 cm (W-7) in **Fig. 8** showed that a reduction of the spacing from 15 to 10 cm increased the output by 28%. Reducing the spacing to 5 cm increased the output by 48% compared to 15 cm. Additional calculations indicated that the increase in output in W/m^2 per centimeter of pipe spacing was highest close to 5 cm. Further increasing the output can be sensible but may not be so efficient. These results show that it is sensible to reduce the spacing down to at least 5 cm if the construction of the system allows it. This is especially important for cooling systems to maximize output while preventing condensation. A dense pipe spacing allows for higher thermal output of the thermo-active surface per energy input to the generator due to the combined beneficial effect of the increase in the power supplied to the pipe and the homogenization of the surface temperature (**Fig. 6**).

Looking at the differences in the maximum and minimum surface temperatures in **Figs. 9** and **10**, it is seen that the surface temperature is largely non-homogeneous, except for the case W-6 with the very dense pipe spacing. The difference between maximum and minimum surface temperature ($T_{\mathrm{surf,max}}$ – $T_{\mathrm{surf,min}}$) was about 3 to 4 K for the cases with a pipe spacing of 10 cm. It was even 7 K for a pipe spacing of 15 cm (W-7). This shows that a dense pipe spacing is important, especially for cooling systems. From the cooling point of view, the nonuniformity in the surface temperature distribution will limit the cooling output of the systems because the minimum surface temperature needs to be above the dew point to prevent local condensation. A higher uniformity of the surface temperature due to a denser pipe spacing allows greater output with a higher water temperature. In other words, the output of the radiant cooling system can be maximized per unit of energy input to the cool source. In addition to a denser pipe spacing, the output could be enhanced and the surface temperature homogenized by using a thermally conductive fin attached to the pipe to improve the temperature distribution. The optimal design of such an element should be the subject of further research.

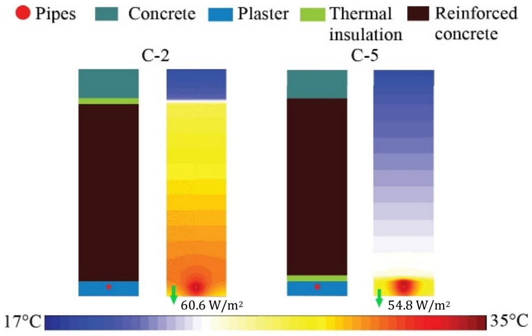

Fig. 4 – Detail of temperature distribution for ceilings

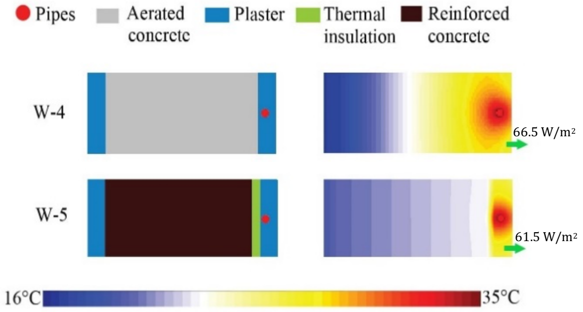

Fig. 5 - Detail of temperature distribution for walls

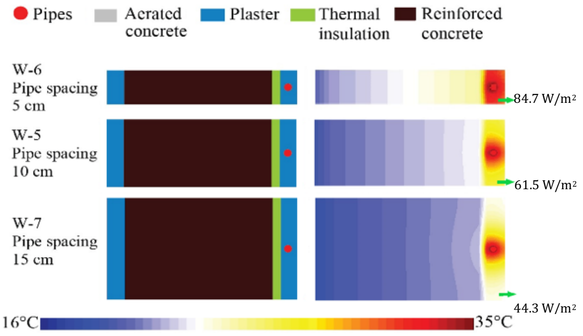

Fig. 6 – Effect of pipe spacing on surface temperature

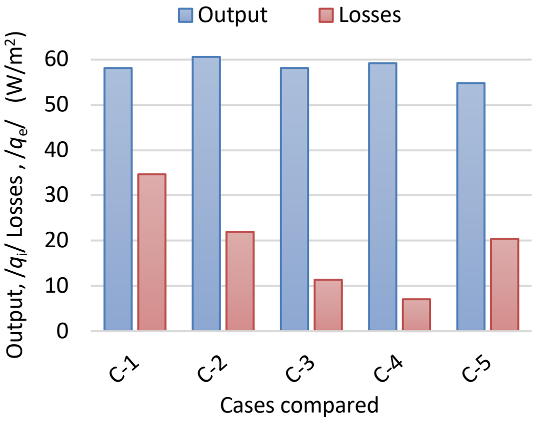

Fig. 7 – Thermal output and losses for radiant ceilings

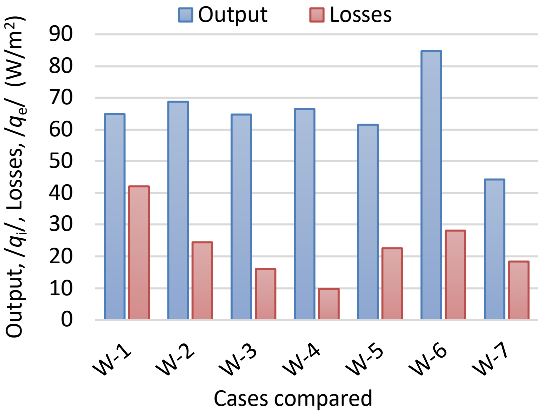

Fig. 8 – Thermal output and losses for radiant walls

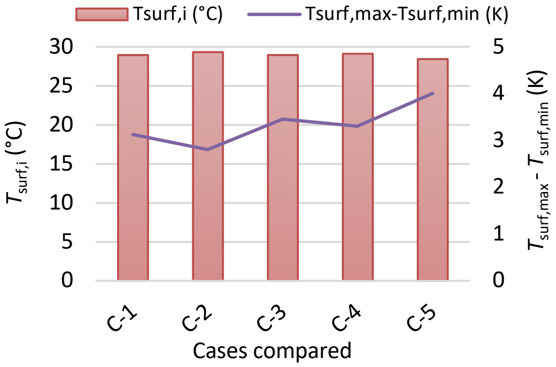

Fig. 9 – Surface temperature for radiant ceilings

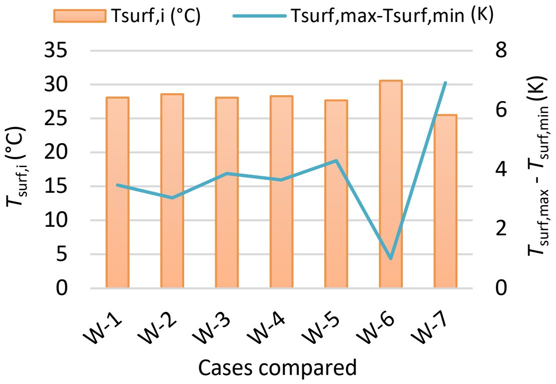

Fig. 10 – Surface temperature for radiant walls

6. Conclusion

This research focused on the effect of the thermal conductivity of the thermal core, the presence and position of the thermal insulation, the spacing of the pipes, and the temperature of the adjoining room on the thermal performance of two radiant heating systems suitable for building retrofit. The main conclusions are summarized as follows:

- With a thermally conductive concrete core, thermal insulation is necessary. For a relatively small temperature difference between rooms, a thin insulation layer (e.g., 1 cm) may suffice. Insulation thicknesses of more than 3 cm may not be efficient.
- If the thermal core is made of an insulating material, thermal insulation may not be needed even at a relatively high temperature difference between rooms.
- A 15 cm pipe spacing was found to be an inefficient design. Reducing the spacing to about 5 cm was efficient in terms in increase in output per 1 cm of spacing.
- For a pipe spacing of 10 cm, the surface temperature was substantially non-uniform due to the pipes located just underneath the surface compared to systems with pipes embedded deeper in the structure. Using a denser pipe spacing made the surface temperature much more uniform. This can be important for radiant cooling systems to achieve greater output while also increasing the required water temperature, thus enhancing the efficiency of the cool source.
- The difference in thermal losses for the placement of insulation on the inner or outer side of the structure was small. However, the output was higher for the insulation placed on the outer side due to a more uniform surface temperature. This configuration also allows considerably higher heat storage capacity.

7. Acknowledgement

This work was supported by the Ministry of Education, Science, Research and Sports of the Slovak Republic grants VEGA 1/0303/21 and 1/0304/21 and KEGA 005STU-4/2021 and Brno University of Technology project FAST-S-22-8060.

The datasets generated during and/or analysed during the current study are not available because of the page limit but the authors will make every reasonable effort to publish them in near future.

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