Can radiant wall cooling be preferable solution for building retrofit?

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Radiant wall systems present a potentially feasible solution for building retrofit which could be preferable to the more common radiant floors and ceilings due to several benefits. The wall systems can be tailored for the specific situation by varying the configuration and thermal properties of the material layers. In this study, we focus on two types of wall cooling systems. The first system has pipes attached to the outer side of the facades of existing buildings. This system was compared with a wall system with pipes embedded underneath the surface in inner plaster. A sample of experimental and computational results is presented to demonstrate the possibilities and limitations of applying these systems in existing buildings. The system with pipes attached to the facades can provide a reasonable thermal output if properly designed. It might be preferable in situations when interventions on the inner side should be avoided. The system with pipes in plaster underneath the surface can be used both on facades and inner walls. Especially when combined with a thermally insulating core made of, e.g., aerated concrete it provides a rapid thermal response and high thermal output and can be very suitable for building retrofit.

Current trends in the design and operation of heating, ventilation and air conditioning include the increasingly frequent use of water-based radiant systems. Installation of such systems can be beneficial due to their suitability for integration with low-grade renewable energy sources such as ground-coupled heat pumps and solar collectors [1,2], comfortable thermal environment [3,4], and relatively high sensible cooling capacity [5]. The applicability of the individual types of radiant systems depends on their location (floor, wall, or ceiling), the configuration of material layers, and the level of thermal mass.

Although research on radiant surfaces has been mostly focused on structural floors and ceilings, contemporary research suggests that radiant walls also present a potentially feasible solution for space heating and

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cooling [6-8]. In a moderate and dry climate and well thermally insulated buildings like, e.g., in Europe, only a fragment of the surface may be needed to create thermal comfort throughout the year [9,10]. This makes radiant walls potentially feasible solution for the retrofit of existing buildings which could be preferable to the more common radiant floors and ceilings due to several potential benefits as discussed in this article.

Nevertheless, scientific studies related to radiant wall systems are relatively scarce. The focus is on new buildings, and the research regarding the use of radiant wall systems in existing buildings as a part of their retrofit is lacking. In this study, we focus on two types of radiant wall cooling systems that could be used in building retrofit. Both systems have pipes attached to the facade, but their configuration of the material layers, thermal performance, and applicability are substantially different. A sample of experimental and computational results is presented to demonstrate the possibilities and limitations of applying these systems in existing buildings.

Benefits and specifics of radiant wall systems

Radiant walls may provide several advantages over floor and ceiling systems:

- Suitability for building retrofit. Adding a radiant wall does not reduce the story height nor does it induce substantial changes in building structures. On the other hand, installing an additional floor or ceiling system reduces the net story height or requires destructing the existing floor.
- Thermal comfort. In certain cases, wall cooling might reduce the risk of thermal discomfort due to cold floors and air temperature gradients in spaces like residential rooms and cellular offices [4,11-13].
- High thermal capacity and rapid thermal response. Wall systems can provide a fast thermal response and good controllability [8]. The cooling capacity is higher for radiant walls (70 W/m²) than floors (40 W/m²), though lower than for chilled ceilings (100 W/m²). The capacity of heating walls is 160 W/m², superior to that of radiant floors (100 W/m²) and ceilings (40 W/m²) [5].
- Several research studies indicate that facades operated as thermal barriers can reduce heat transmission through walls, thus preventing heat losses in winter [14-16] and absorbing external heat gains in summer [17,18].

Radiant walls have certain specifics pertaining to their construction and operation that need to be considered. If installed on the outer side of existing buildings, they are subject to daily and seasonal weather variations. Especially in summer, these variations may be complex because of the fluctuating solar radiation incident on the facade. Compared to floor and ceiling systems, the disadvantage of walls could be the lower angle factor between the occupant and the wall and that interventions need to be done with caution to prevent damaging the pipes.

Wall cooling with pipes attached to facades

The first technology presented is a wall cooling system constructed according to a patent [19]. The patented design involves pipes arranged in milled channels in thermal insulation, whereby panels are formed. The potential benefit of this system is the possibility to attach the panels to the facades of existing buildings as a part of retrofit with only minor interventions on the interior side of the buildings. The system can be operated both as space cooling in summer and as space heating in winter. Moreover, it could potentially serve as a thermal barrier to reduce transmission heat losses in winter and heat gains in summer [14]. Laboratory measurements were performed for the wall system "as patented" and subsequently an optimization study was carried out to enhance the thermal output.

Laboratory measurements

The laboratory measurements were conducted on an experimental wall fragment. The fragment consisted of cooling pipes embedded in milled channels in thermal insulation made of polystyrene, attached to the concrete core in the form of a panel. The dimensions of the fragment were 1140 mm × 1360 mm (**Figure 1**). The temperature of the concrete was monitored by PT100 platinum resistance thermometers with the accuracy variable in the range of ±0.15°C, located at selected points along the panel (points A, B, C, D in **Figure 1**) at several depths (points 1 to 5 in **Figure 1**). Supply and return water temperature were also recorded. The heat flux was monitored by a thermopile sensor for studies of the radiative and convective heat flux with a level of accuracy variable in the range ±5% of the value measured. The sensor was located underneath the surface in the centre of the fragment.

The wall was located between two climate chambers with controlled air temperature and humidity (**Figure 2**). The fragment was exposed to the air temperature of 32°C simulating ambient conditions on one side, and to the air temperature of 26°C simulating the room conditions on the other side. Direct solar radiation was not considered in this study. The temperature of the supply water was kept constant at about 18°C. The heat transfer coefficients between the surface of the wall and each chamber were calculated by a CFD simulation in ANSYS Fluent [20]. A heat transfer coefficient between the wall surface and room of 12.5 W/(m²K) was considered representative of the experimental conditions, which is higher than the 8 W/(m².K) as recommended for the design of radiant wall systems [21].

Design optimization

The temperature and heat flux distribution within the wall fragment were visualized using CalA software developed by one of the authors to solve 2D unsteady heat conduction in building structures [22]. The software has been verified following EN ISO 10211 [23] and EN ISO 11855-2 [21]. The heat transfer analysis was carried out using the Finite Volume Method. The implicit Euler scheme was used for the temporal discretization. The Gauss-Seidel iterative method with successive over-relaxation approach was employed to solve the resulting

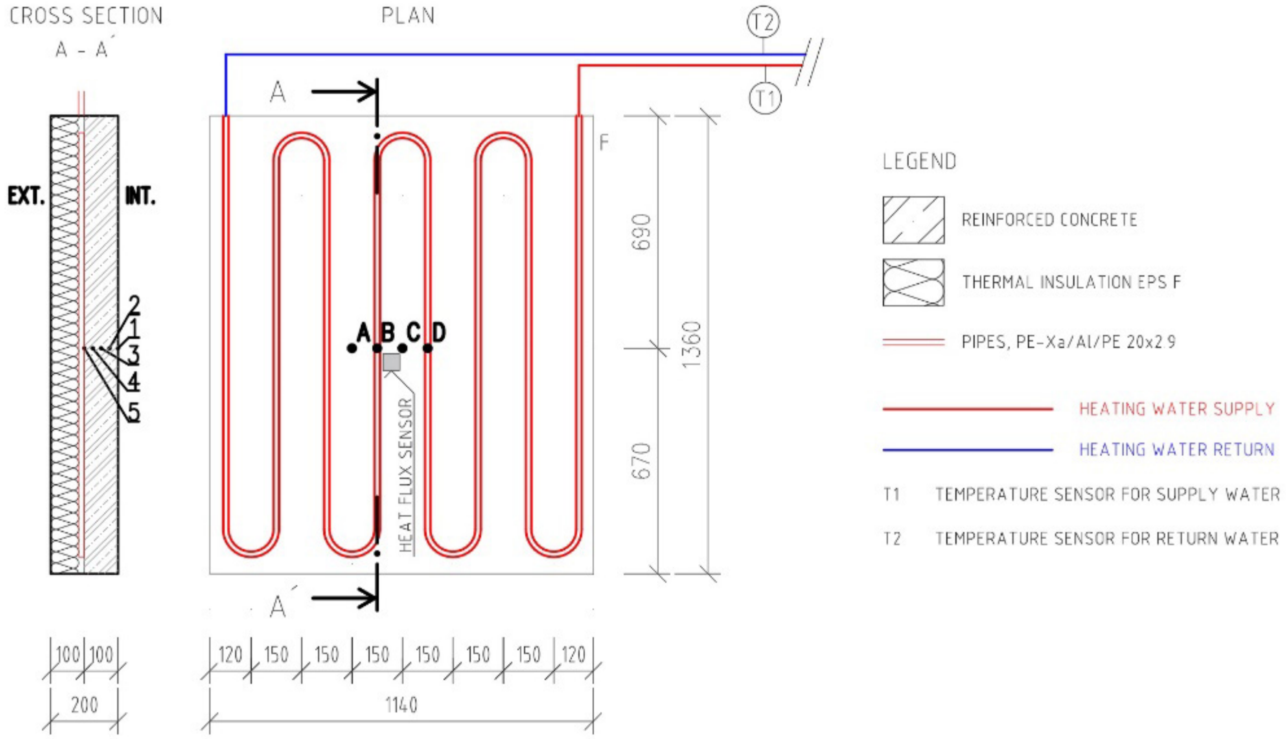


Figure 1. Details of experimental wall and location of sensors [20].

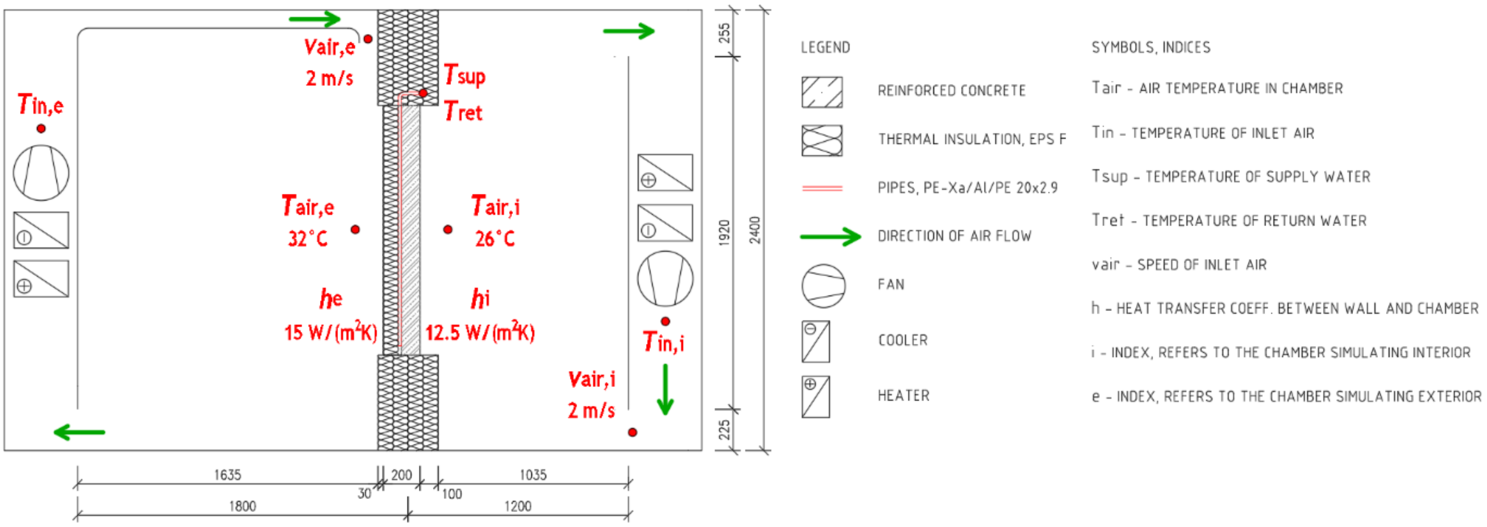


Figure 2. Cross-section of experimental chambers and location of sensors [20].

system of linear equations. The heat transfer coefficient between water and pipe was 1218 W/(m².K). 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 boundaries of the wall fragment (**Figure 3**). The red arrows indicate the direction of the cool transfer. Validation of the computer model by the experiments can be found in Ref. [20]. **Figure 4** shows the simulation model as defined in the CalA software.

The simulations and experiments proved that imperfections in the contact between pipe and wall hinder the heat transfer between the pipe and the thermal core. The possibilities to improve the patented design were therefore investigated. The optimization study refers to the room temperature of 26°C and the mean water temperature of 21°C. The total heat transfer coefficient (h_i) between the radiant surface and space was 8 W/(m².K), and the heat transfer coefficient between water and pipe was 1218 W/(m².K). The combined effect of ambient temperature and solar radiation incident on the wall was approximated by the sol-air temperature ($T_{\text{sol-air}}$) [24] equal to 57°C which corresponds to the ambient temperature of 30°C and solar radiation incident on the wall of 450 W/m².

The improvements to enhance the cooling output were represented by inserting a metal fin between the pipe and thermally conductive plaster. The purpose of the fin was to efficiently distribute the cool from the pipe to the thermally conductive plaster. **Figure 5** illustrates the difference in the cooling output between a wall fragment without any fin (a) and with a fin with a thickness of 1.56 mm, made of copper (b). Adding the metal fin enhanced the cooling output by about 50% due to the improvement of cool distribution within the wall as shown by the larger dark blue (cool) area between pipe and interior (**Figure 5a**) and the homogeneous heat flux distribution (**Figure 5b**).

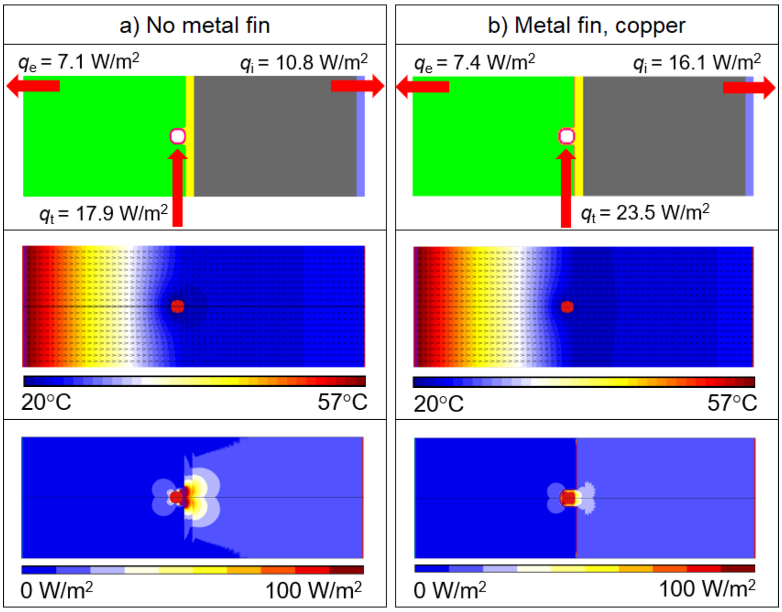


Figure 5. Temperature and heat flux distribution within the wall fragment: a) without metal fin, b) with metal fin made of copper, thickness 1.56 mm, thermal conductivity 372 W/(m.K) [20].

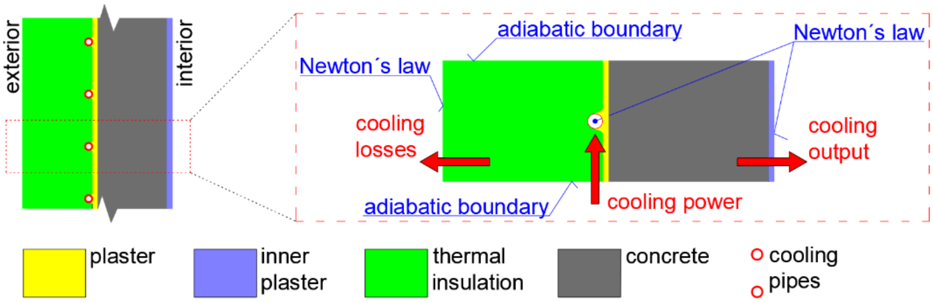
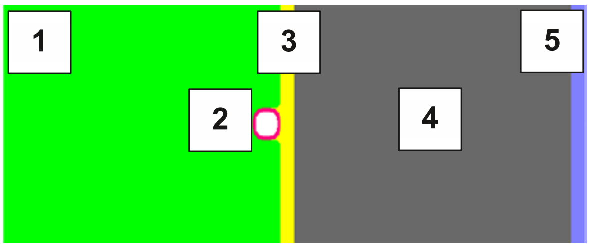


Figure 3. Boundary conditions defining specific heat flux on a wall surface [20].



(1) Insulation: d = 0.02 m, λ = 0.04 W/(m.K), c = 1270 J/(kg.K)
(2) Pipe ø 20: λ = 0.35 W/(m.K), c = 1000 J/(kg.K)
(3) Plaster: d = 0.01 m, λ = 0.8 W/(m.K), c = 840 J/(kg.K)
(4) Reinf. concrete: d = 0.2 m, λ = 1.58 W/(m.K), c = 1020 J/(kg.K)
(5) Inner plaster: d= 0.01 m, λ = 0.88 W/(m.K), c = 840 J/(kg.K)

Figure 4. Physical model of the wall fragment as defined in calculation software.

Figure 6 shows the heat flux on the interior side (thermal output) for three materials of the metal fin – copper (q_{i_Cu}), aluminium (q_{i_Al}), and steel (q_{i_steel}). Five cases were considered for the fin made of copper which was most efficient in terms of cool distribution. Three cases were considered for aluminium and steel to allow comparison. The difference between the fins made of aluminium and copper was small regardless of the fin thickness. Increasing the fin thickness had minor effect on the thermal output. Fin made of steel was the least efficient. In this case, the thermal output was most sensitive to the fin thickness.

Wall cooling with pipes underneath the surface

The wall cooling system with pipes attached to the facade (System A in **Figure** 7) was compared with a wall system with pipes embedded underneath the surface in plaster (System B in **Figure** 7). Compared to Section 3, the design of System A was modified so that the cooling pipes were embedded in plaster between thermal core and thermal insulation. System B can be used for building retrofit because the active layer containing the pipes can be easily attached to an existing wall structure.

The results presented in this section were elaborated using the CalA software. The calculation model was based on the validated model described in Section 3 and the properties of the materials were nearly identical. The spacing of the pipes was 150 mm. The overall heat transfer coefficient was 8 W/(m².K) on the inner and 15 W/(m².K) on the outer wall´s surface. The heat transfer coefficient between water and pipe was 1218 W/(m².K). The room temperature and mean water temperature was 26°C and 20°C, respectively. The average daily sol-air temperature which combines the effect of ambient temperature and solar radiation incident on the wall was 41°C. This sol-air temperature is representative e.g. of a southern wall in the temperate climate of Central Europe in July.

Temperature and heat flux distribution

The temperature and heat flux distribution are visualized in **Figure 8** for two materials of thermal core – a thermally insulating aerated concrete and a thermally conductive reinforced concrete. The yellow arrows indicate the general direction of the cool transfer. The thermal output of System A was low because of

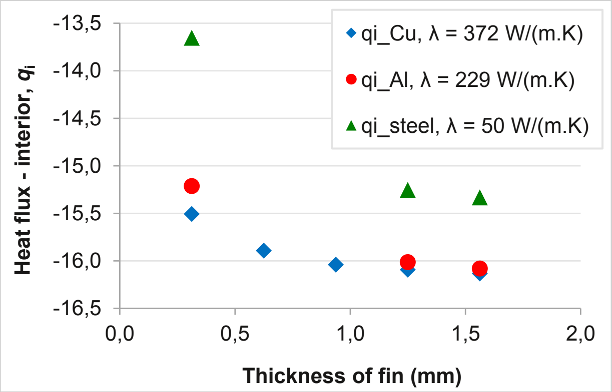


Figure 6. Cooling output of the wall fragment for variable thickness and materials of the fin [20].

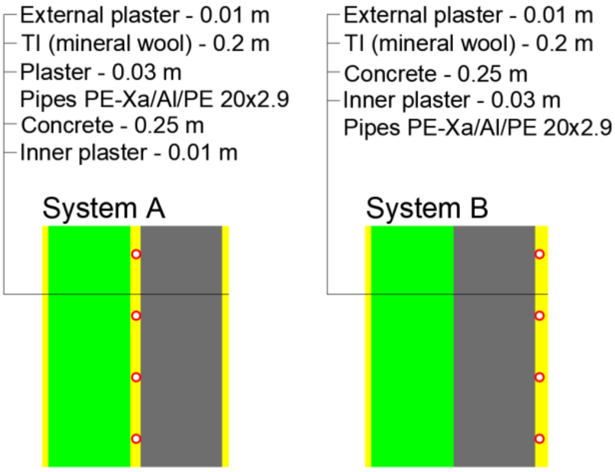


Figure 7. The two wall cooling systems studied.

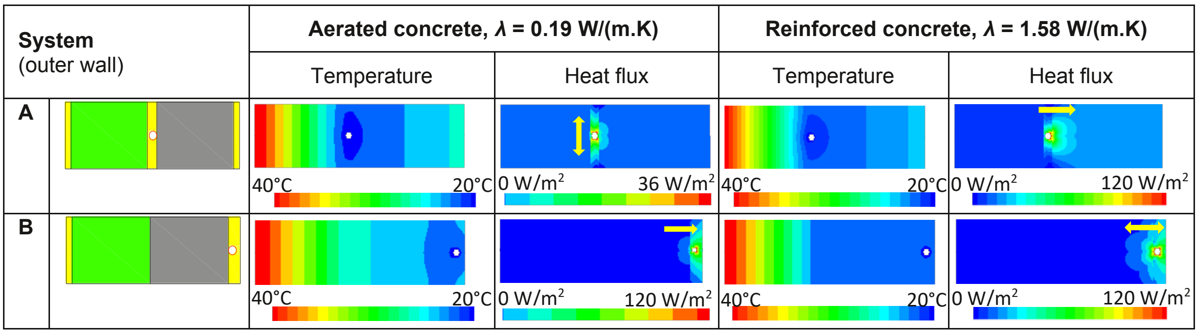


Figure 8. Temperature and heat flux distribution for the cooling systems located on an external wall [8].

the cooling losses and the cool being accumulated in the concrete core. As expected, this system makes sense only with thermally conductive core, otherwise, the thermal output is too low.

For System B, both aerated and reinforced concrete are meaningful, but the core material has a substantial effect on the heat transfer. With aerated concrete, the cool is directed to the interior, whereas with reinforced concrete the cool is distributed in the structure more evenly which leads to more cool being stored. System B with aerated concrete can be therefore efficient even without any insulation on the outer side of the wall. The maximum thermal output was higher in the case of reinforced concrete because the cool was distributed more evenly in the structure which resulted in more homogeneous surface temperature and consequently higher output.

Thermal response

The effect of core material on the thermal response of the systems was observed as well. Thermal response of radiant systems significantly affects their controllability, operating strategy, and overall applicability. In the tests, the cooling system was powered on at 9:00 and turned off at 17:00 o´clock. A control strategy was devised where the thermal output was kept between 63% (q_{63}) and 90% (q_{90}) of its maximum value by turning the cooling system on and off. Although simplified as compared to real operating conditions, this control strategy permits evaluating thermal response and controllability of the wall systems [8].

The response of System A was always slow due to the thermal coupling of the pipes and the thermal core, and the distance of the pipes from the interior. **Figure 9** shows that concrete properties are crucial for the thermal dynamics of System B. The combination with reinforced concrete resulted in a slow thermal response. On the contrary, the aerated concrete acted as thermal insulation and directed the cool to the interior causing a faster thermal response.

Conclusion

Radiant wall systems can be readily installed in existing buildings as a part of their retrofit. The various combinations of thermal properties and configuration of the material layers allow tailoring the wall system for the specific situation. The suitability of a specific wall cooling solution depends on the requirements such as avoiding interventions in the interior, exploiting thermal storage, ensuring high thermal output, or providing a fast thermal response.

Two representatives of the wall systems potentially suitable for building retrofit were presented. It was shown that System A with the pipes attached to the outer side of a facade can provide a reasonable thermal output if properly designed (adding metal fin between pipe and core or embedding the pipes in thermally conductive plaster). Though this system has a substantially lower thermal output than System B, it might be preferable in situations when interventions on the inner side of the wall should be avoided.

System B with pipes embedded in plaster underneath the surface can be used both on facades and inner walls. If the wall´s thermal core is made of an insulating material such as, e.g., aerated concrete, no thermal insulation may be needed on the outer side of the wall. Thermal

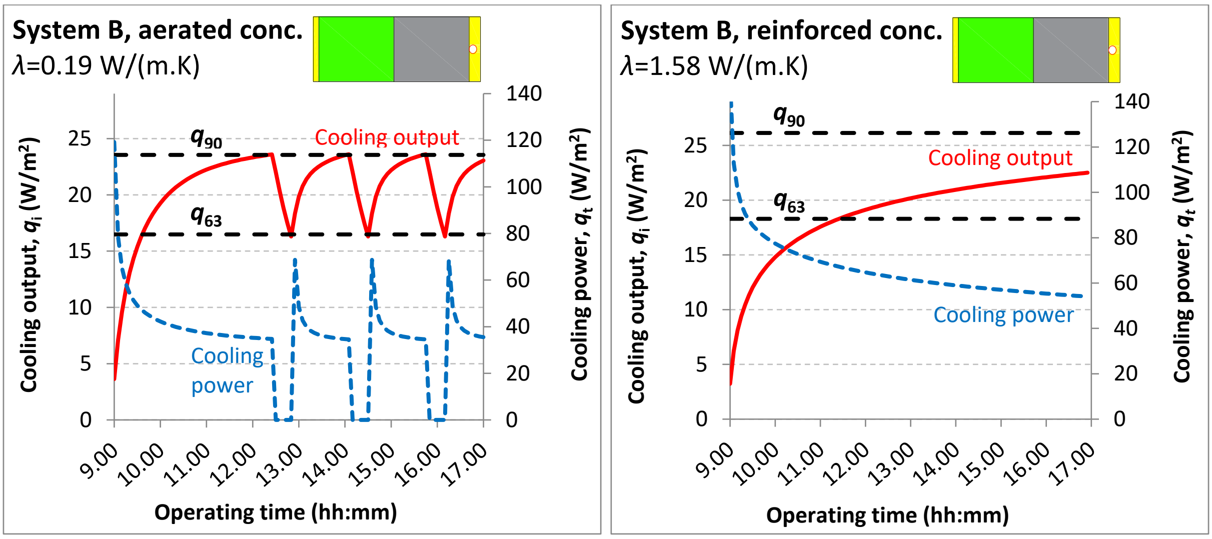


Figure 9. Effect of core material on thermal response of System B [8].

losses of such a wall system are low, it has a rapid thermal response and high thermal output which makes it suitable for installation in both new and existing buildings. In case of a thermally conductive core, similar system characteristics can be achieved by adding a layer of thermal insulation between pipes and the core. ■

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