Are radiators ready for the challenges of the future: A review of advancements in radiators

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Abstract. Radiators play an important role in providing a comfortable and safe indoor environment while maintaining high-energy efficiency. In the perspective of future climate change with expected larger temperature fluctuations and the rapidly changing heat supply and demand, it is required that the current radiator technology is adaptable. The heat supply is changing towards a lower supply temperature to enable an increase in energy efficiency and an increase in the share of renewable energy. Simultaneously, both the heat supply and demand are expected to have more variations in the future. An additional concern that has come into more focus after the experience with the COVID 19 pandemic is the prevention of the spread of infection in indoor environments. Researchers have extensively studied several innovations in radiator technologies and their deployment that addresses these challenges. Some of the solutions available in the literature include floor heating, ceiling heating, ventilation radiator, stratum ventilation. Researchers have used advanced modeling and experimental techniques to understand how to deploy different types of radiator technologies. This review summarizes solutions in the literature that address these challenges and identifies knowledge gaps that need to be addressed. In particular, this study explores the gaps in knowledge of practical issues, such as the position of furniture and the position of people, which have received less attention in the literature. Research that addresses the effect of radiators on ventilation and a healthy indoor environment is also of particular interest in this review.

1 Introduction

Lowering the temperature requirements of a heating system has several advantages to improve the heat supply. A lower supply temperature for heating based on district heating will reduce the distribution of heat losses and increase the electrical power generated in combined heat and power plants [1]. For houses heated using heat pumps, a lower supply temperature will increase the efficiency of the heat pumps. Moreover lowering the supply temperature enables the use of low-temperature heat sources from waste heat and renewable sources.

One of the ways to ensure thermal comfort in buildings supplied with low-temperature heat supply is to replace the radiators with low-temperature radiators. Østergaard and Svendsen [2] showed that the lowering of supply temperature can be achieved by identifying and replacing the critical radiators in a building. Therefore, there is a growing interest in the development of radiators suitable for low-temperature supply. In this review, we present some of the technologies used for low-temperature heat supply in section 2, studies that focus on the effect of the position of radiators and the presence of furniture and occupants in the room are presented in section 3, and the effect of low-temperature radiators on the indoor air quality is presented in section 4.

2 Low-temperature radiators

Radiator technology has been evolving to adapt to a lower supply temperature while ensuring good thermal comfort and indoor air quality for the occupants. As a result, several low-temperature heating technologies like floor heating, ceiling heating, wall heating, thermal skirting, ventilation radiators, and stratum ventilation heating, have been studied and improved. An extensive comparison of low-temperature heating solutions with high-temperature heating found that low-temperature devices can provide better indoor air quality and better comfort [3]. Studies show that people living in houses with low-temperature heating are more satisfied with the indoor climate compared to people living in houses with high-temperature heating [4].

Floor heating is one of the oldest and most studied low-temperature heating technology. Radiation provides a significant portion of the heat in floor heating. Hence such radiators are also referred to as radiant heating systems. Radiant heating systems have been shown to provide the same level of comfort as a convective heating system with a lower energy requirement [5]. Recently, Micko et al. [6] performed CFD simulations of a radiator and floor heating scenarios and concluded that floor heating can provide a more comfortable indoor environment as it has a higher mean radiant temperature for the same indoor air temperature. Floor heating can be combined with conventional radiators to provide the required comfort using a low-temperature supply even with an outdoor temperature of -26^{0}C [7].

Other forms of radiant heating are wall and ceiling heating which use a wall or ceiling instead of the floor as the radiating surface. Karabay et al.[8] compared wall and floor heating through numerical models. They found that

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the temperature distribution is more homogeneous for floor heating but it produces strong circulation that may cause discomfort. Although the temperature was less homogenous for wall heating, it only caused weak circulation that does not cause discomfort. A risk with both floor heating and wall heating is the formation of cold droughts near the floor [9,10] which must be countered to provide thermal comfort. Ceiling heating systems have the advantage that they are not covered by furniture or carpeting. However, floor heating has a lower distance between the radiating surface and the human body hence they have a higher heat exchange rate [11]. Ceiling heating systems might not be sufficient in cold climates hence Koca and Çetin [12] recommended a combination of wall and ceiling heating systems for colder climates. The comfort level is often measured based on the predicted mean vote (PMV) model [13]. However, an experimental study showed that the actual thermal comfort in a radiant cooling system was higher than the value predicted by the PMV model [14]. Although there have been several studies on radiant systems a review of the studies showed that only 3 studies conclusively show that radiant systems provide better comfort than conventional systems [15]. Hence, more investigations into radiant systems are justified.

Skirting boards/baseboards are another low-temperature heating device that has been studied. Ploskić and Holmberg [16] used CFD models to show that thermal skirting boards can satisfy the heating rooms using a low-temperature supply. However, they found that a low-temperature supply creates a cold drought near the floor even in the case of skirting boards. Combining heating devices with ventilation has been studied extensively. The advantage of this strategy is that they are easy to implement using the devices present in the market. Myhren and Holmberg [17] performed CFD simulation for regular radiators and ventilator radiators and showed that ventilator radiators can achieve a more stable temperature and the radiator temperature can be lowered. The performance of ventilation radiators was also assessed for a standard room with a standard air vent [18]. An experimental study comparing floor heating, ventilator radiators, and conventional radiators for the Danish climate showed the potential of ventilation radiators and floor heating to reduce the supply temperature [19]. The supply temperature could be reduced from 45^0C to 33^0C and 30^0C using ventilation radiators and floor heating respectively. Liu et al. [20] compared stratum ventilation heating, in which the air is heated in the air handling unit instead of the room, with floor, ceiling, and wall radiator and showed that stratum ventilation can provide satisfactory indoor thermal comfort with better energy and exergy performance.

3 Effect of radiator position, furniture and occupants

The position of the radiator can affect the local thermal comfort in a room. Traditionally the radiators are placed near the window to counter the effects of the window. However, the heat loss from windows has been reduced in recent years, hence this position of windows can be questioned. A CFD simulation of a room with two radiator positions, one below the window and the other on walls away from the window found that the average temperature was higher when the radiators were away from the windows [21]. Another study compared a radiator next to the window with a radiator on the roof and found that placing the radiator on the roof is more energy efficient while placing the radiator near the window is better for thermal comfort[22]. Mirmanto et al. [23] studied the effect of radiator position in an experimental setup with no windows. They placed the radiator near the wall, in the center of the room, and on the floor. The case with the radiator on the floor was shown to have the highest heat transfer coefficient

Wall-mounted radiators can lose up to 5% of heat from the wall behind the radiators [24]. The use of metallic foils [25] or radiation shields [24] with low emissivity has been shown to reduce this loss by around 30%. Jahanbin and Zanchini [26] showed that increasing the distance between the wall and the radiator to 10cm will improve the performance of the radiator.

In most studies, radiator performance is evaluated in empty rooms. However, the presence of furniture can affect the flow of air in the room and reduce radiation heating. Hence, studies that consider the furniture in the room can provide important insights. Wolisz et al. [27] modeled a room with and without furniture. They showed that the effect of the furniture was not important in steady-state models but the dynamic model showed that a room without furniture heats up significantly fasters than a room without furniture. Other studies have also shown that it is important to consider the thermal mass of furniture, especially in lightweight structure buildings [28,29]. The furniture is usually represented by simplified geometries in such analysis [30–32]. Wallentén [33] measured the heat transfer coefficient of walls of a room with and without furniture the effect of the furniture was not significant in this study. Horikiri et al. [34] also studied the effect of furniture and found that the furniture did not change the temperature field but caused high local air velocities. Furniture might have a higher influence on radiant heating systems, experimental studies on a scaled model showed that the heat flux from a floor heating system was reduced by 30% when 40% of the floor was covered by furniture [35]. Peng et al. [36] studied the ceiling, sidewall, and ceiling-sidewall composite heating systems using experimental and numerical studies. They found that the presence of furniture can reduce the local temperature by up to 1.2^0C.

The presence of occupants in a room can also have a significant influence on the temperature and velocity fields. Hence, a numerical model that can accurately simulate the presence of a human has been developed [37]. A CFD simulation of an office with humans, computers, and furniture showed a temperature increase of 22-25% higher than the case of an empty room [38]. Horikiri et al. [34] also showed that adding occupants to a room changed the temperature field enough to cause discomfort to the occupants.

4 Indoor air quality for low-temperature heating

Changing the heating device in a room will change the flow patterns and affect ventilation in a room. Therefore, it is important to consider the effect of low-temperature heating devices on indoor air quality. Some studies have shown that low-temperature devices can provide better indoor air quality compared to high-temperature solutions [3]. The air temperature can be lower in a radiant heating system for the same comfort level, which leads people to perceive the air quality to be better [39]. Additionally higher surface temperature in floor heating reduces the risks of condensation and mold growth [40]. A recent study [41] showed that increasing air supply to meet the recommendations post COVID using a conventional cooling system would significantly increase the cooling demand. Whereas using a combination of radiant cooling and natural ventilation to satisfy the new recommendation will reduce the energy demand.

Low-temperature radiators also have an advantage when it comes to particles. Golkarfard and Talebizadeh [42] compared the particle deposition in a room with a radiator and floor heating using numerical simulations. They found that the floor heating had lower particle deposition and that floor heating deposits particles on the ceiling while radiator heating deposits on the floor. Dehghan and Abdolzadeh [43] performed 3-D simulations of airflow and particle deposition in a room with a manikin. They compared floor, skirting board, and radiator heating and concluded that skirting board heating had the least particle concentration in the breathing zone.

A risk with radiant heating is a higher emission of formaldehyde and volatile organic compounds due to the higher temperature of the surfaces [44,45]. The process of 'bake-out', i.e., heating the room to a high temperature and removing the VOC before using the room, can reduce this risk[46].

5 Conclusion

The literature review concludes that the low-temperature heating devices can not only deliver the required amount of heat with a low supply temperature. They can also improve thermal comfort and indoor air quality. However, there is a limited number of studies that address the issue of how the presence of furniture and occupants affects the performance of low-temperature radiators. Hence, a better understanding of this aspect is required to determine the design and position of radiators. Although there have been a few studies on the effect of low-temperature radiators on indoor air quality, the studies have been limited to particle matter and VOCs. Other risk factors like the spread of aerosols also need more attention.

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