Study on Floor Heating Systems Influenced by Intrinsic and Extrinsic Factors - A Review

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Abstract
Since the Covid-19, people are increasingly inclined to work from home. The expectations regarding comfort have made many requirements on the indoor environment. In winter, floor heating systems (FHS) show great advantages in terms of thermal comfort. However, the intrinsic thermal mass has a significant effect on the response time. The needs of the occupants are not only for a comfortable air temperature, but also for the moderate indoor humidity and warm sunshine. With the slow thermal response, these extrinsic factors may induce the thermal comfort degradation. This review paper aims at discussing the influences of these intrinsic and extrinsic factors on FHS and indoor environment to help researchers to conduct relevant studies.

Highlights
- Thickness and material of the cover and slab, and the water flow velocity are the primary influencing factors on the thermal response
- Solar radiation is an extrinsic factor that cannot be overlooked
- Competition between humidification and heating process probably leads to the overheating of floor surface
- Solutions for easy application should be further explored

Introduction
The worldwide energy consumption is increasing rapidly, which is leading to large amounts of depletion of natural resources and emissions of greenhouse gases. According to the International Energy Agency (IEA) (2022), buildings account for almost one-third of final energy consumption globally and are an equally important source of CO2 emissions, and nearly half of the energy consumption is from space heating and cooling, as well as hot water. Therefore, the developments of energy-efficient heating and cooling technologies have become critical strategies to ensure sustainable development. Besides, since the Covid-19, people are increasingly inclined to work from home, and a higher level of indoor comfort is also demanded.
To build better living and working conditions for occupants, various building heating, ventilation, and air conditioning (HVAC) systems have been widely employed (Jiang et al., 2020; Zhang et al., 2020). Compared with conventional heating methods, there has been an increase in the use of radiant heating systems in order to improve the indoor thermal comfort and the energy efficiency (Sun et al., 2020; Yan et al., 2022; Xu et al., 2010; Olesen, 2002).

One limitation of FHS is that it is difficult to handle latent heat loads in humid regions and also pollutants in heavily polluted regions. As a result, ventilation systems are typically combined to overcome the shortages which are studied in (Gu et al., 2021; Li et al., 2020; Yan et al., 2022). The other limitation is the long response time caused by large thermal inertia of the floor (Rhee et al., 2017; Zhao et al., 2014). Due to the latter weakness, when the system is subjected to sudden increase in heating or cooling loads, slow thermal response may induce thermal comfort degradation.

For example, a floor heating system will provide more hot water to heat a room due to a large response delay thus leading to a larger air temperature deviation from the set point. The heating demand can be induced by the opening of windows in winter to renew air or humidification needs (Lin et al., 2016; Zhang et al., 2020; Feng et al., 2018), which might induce the overheating of the floor surface. Solar radiation is also an extrinsic factor that cannot be overlooked, especially in the sunny cold days during heating season.
The thermal masses of heating slabs, as an intrinsic impact factor, usually have a large thermal inertia and result in a long response time. In order to reduce the response time, the researchers have carried out numerous studies. However, when it comes to the extrinsic impact factors (the common phenomena in residential buildings like the sun patch and cool mist humidification), only few researches have been done.

Up to now, no work has been found within the literature with a combined analysis of the different impact factors on floor heating systems.
Thus, the objective of this paper is to summarize the researches of floor heating systems, including all of these intrinsic and extrinsic factors, and try to highlight the influences from extrinsic factors in order to attract more relevant researches.

Influence of thermal mass
The thermal mass in embedded systems has a significant effect on the response time and heating capacity of the
system and hence on the control strategy. Many researchers have been working on the structural improvement of radiant slabs (Merabtine et al., 2019; Brideau et al., 2020; Merabtine et al., 2018; Sattari and Farhanieh, 2006; Zhang et al., 2013; Zhou and He, 2015; Ding et al., 2020). Sattari and Farhanieh (2006) performed the parametric study on a floor heating system using finite element method. The results showed that the cover thickness and material parameters have considerable effects on the thermal performance of the floor heating system, but the effects, of pipe material, diameter and their number, are minimum. Merabtine et al. (2018, 2019) conducted a sensitivity study based on the DoE method and found that the thickness and material of the slab and the water flow velocity are the primary influencing factors on the thermal response of the FHS. Similarly, the influence of the tube inner diameter is not significant.

The radiant slabs of FHS can divide into two types, the heavy and the lightweight slabs. The pipes of heavy systems are usually embedded into the concrete or screed layer of the floor construction, however, in the lightweight systems, the pipes are placed in the air interlayer between a top surface layer and a bottom aluminum foil as shown in Figure 1 (Zhang et al., 2013), which allows the system to respond quickly due to the low thermal mass. Zhang et al. (2013) analyzed the influence of pipe spacing of a lightweight floor heating system and concluded that the floor surface temperature and indoor air temperature decrease when the pipe spacing increases. Brideau et al. (2020) evaluated the time response of four different radiant floor constructions: one tube-in-subfloor (a type of above floor tube-and-plate (AFTP) system) shown in Figure 2, and three embedded-tube systems shown in Figure 3, in which the thickness of the gypsum cement or concrete are 3.8cm and 8cm, respectively, and for the systems with 8cm slab thickness, one with the tubes at the bottom of the slab, and the other one with the tubes near the top of the slab. The results showed that the response of AFTP system is the quickest, followed by the 3.8cm slab. The embedded-tube case with the tubes near the bottom of the slab is the slowest one to respond.

Zhou and He (2015) experimentally investigated the thermal performance of a floor heating system with different thermal mass (sand and phase change material (FHS)) and heating pipes (polyethylene (PE) coils and capillary mat). The floor structures are shown in Figure 4. Compared with PE coils, the capillary mat gives more uniform vertical temperature distribution and shorter charge time. The FHS provides less temperature variation in floor and needs twice longer charge time compared with the case of sand. Nevertheless, the FHS offers twice longer discharge time than the case of sand to keep the indoor temperature in comfortable range. For further energy saving, a floor heating system combined with FHSM has attracted some interests (Lu et al., 2018; Yun et al., 2019). Capillary radiant floor systems have a smaller pipe diameter and spacing (Jobli et al., 2019). This type of structure allows it to respond faster to the change of room temperature (Cho et al., 2019; Mikeska and Svendsen, 2015; Kim et al., 2002). Cho et al. (2019) compared the thermal performances of the conventional Korea standard radiant floor heating system with polybutylene pipe (PB) and the low-temperature system with capillary tube (CT) by experiments and simulations. Compared to the case with PB, the case with CT has a very uniform temperature distribution for the floor surface. Also, the case with CT takes three times shorter response time than the case with PB for the initial indoor air temperature to rise by 4°C. Ding et al. (2020) analyzed the influencing factors
of the heating capacity of capillary radiant floor heating systems by a simplified thermal model. The floor structure is shown in Figure 5. The results showed that the heat flux increases with the increasing of the thermal conductivity of surface layer and decreases linearly approximately with the increasing of the pipe spacing. In addition, the filling material with higher thermal conductivity can increase the heating capacity through the floor surface. The heat flux increases slightly when the thermal conductivity of pipe material changes from 0.4 W/(m·°C) to 2 W/(m·°C).

![Figure 4: Schematic of the floor structure layers (Zhou and He, 2015). (a) PE coil as heating pipes; and (b) capillary mat as heating pipes.](image)

![Figure 5: Schematic of radiant floor with multilayer structure (Ding et al., 2020).](image)

By considering all the above, it is easy to understand that selecting a suitable thickness for heating slabs that satisfies both fast-response and energy-saving requirements can be a difficult task. Apart from the thickness, the material of the cover and slab, and the water flow velocity in pipes are also the primary influencing factors on the thermal response of the FHS, but the effects of pipe material and diameter are not significant.

**Influence of solar radiation**

The solar heat gains through the windows are often neglected in cold climate regions where reducing heat loss and requiring heating energy is the primary goal, while the effect of solar radiation on thermal comfort is more severe in these regions (Song et al., 2022). For floor heating systems with large thermal inertia and high floor temperature, sun patches are likely to cause the overheating of floor surface. A few researches have been carried out to address the solar radiation concerns in a floor heating system. Athienitis and Chen (2000) presented a detailed study of solar radiation effects on floor heating systems by employing a three-dimensional explicit finite differential model (a sinusoidal outdoor temperature profile was assumed with a mean of -10°C and an amplitude of 5°C, which is typical in January in Montreal), and found that the incident solar radiation on the floor caused a temperature difference of up to 8°C between the illuminated and shaded areas. Benzaama et al. (2016) developed a TRNSYS-FLUENT coupled model to simulate the effect of the sun patch on the heating floor under transient climatic conditions based on the climate in Oran, Algeria, which is influenced by the Mediterranean climate with mild and wet winters. The average outdoor temperature is around 5°C in January. Figure 6 shows the movement of the sun patch and its effects on the temperature of the heating floor surface. The local floor overheating can be observed.

![Figure 6: Effect of the sun patch on the thermal behavior of the heating floor (Benzaama et al., 2016).](image)

An experimental study of the effects of a moving sun patch on the indoor environment is often not only limited by weather conditions, but also by the difficulties of repeating the experiment. Olesen (1994) used electrical heated blankets placed on the floor to simulate solar, occupant and lighting gains in order to compare the ability of controlling of different heating systems. Beji et al. (2020) carried out an experimental work on the impact of various locations of the sun patch on the thermal response of FHS by using a heating film to simulate the sun patch. The study was performed in Troyes, France, which belongs to a temperate oceanic climate, and the outdoor temperature was fixed at 5°C based on the local weather data. They observed a floor surface overheating due to the direct solar radiation, which was set to 700 W/m² representing the solar intensity on a clear sky day in winter.

Li et al. (2023) proposed a new method to simulate the moving sun patch by heating films in experiments and evaluated the indoor thermal comfort by a thermal manikin. This study was conducted in the same test cell with Beji et al. (2020). In the case with 11.6% of window-to-wall ratio (WWR), the solar radiation decreases the indoor thermal comfort compared with that
in the case with 5.8% of WWR according to the thermal manikin as shown in Figure 7.

![Figure 7: Dynamic thermal comfort and sensation (Li et al., 2023).](image)

Although the above studies were conducted in specific climatic zones, other than tropical and polar climates, the results can still be applied to other climatic zones where there are cool or cold winters and a certain amount of solar radiation. It also can be seen that solar radiation will induce the local overheating of floor surface and a consequent reduction in the overall indoor thermal comfort. In the future, various ways of mitigating overheating caused by sun patch should be actively explored while ensuring indoor light comfort.

As an inevitable extrinsic impact factor, most research remains in simulation, and experimental studies are very limited. Even in experiments, due to constraints imposed by weather conditions, a heating film is still used to simulate the sun patch. If conditions permit, experiments with real sun patches can be carried out in an outdoor laboratory as a supplement to the research data.

**Influence of cool mist humidification**

Indoor temperature and humidity are two important parameters affecting the thermal comfort in buildings. The effects of humidity on thermal sensation are rather limited compared to air temperature based on ISO 7730:2005 and CEN-EN15251 (2007), while low relative humidity probably causes dryness of the eyes and skin, and even exacerbates symptoms in the upper and lower airways (Lukesio et al., 2016; Sunwoo et al., 2006). Jin et al. (2020) carried out a field study and found that a minimum humidity of 41% could be predicted to avoid dry skin for elderly people in care homes if the room temperature is maintained at 21 °C. Cold and dry environments also facilitate the survival and spread of viral diseases, and some studies observed air humidity negatively correlated with Covid-19 morbidity and mortality (Biktasheva, 2020; Ma et al., 2020).

Camuffo (2019) calculated the decrease in RH induced by heating systems in 211 European cities under the assumption that the outdoor RH remained equal to 100%. The results showed that in most buildings indoor RH attained levels below 30% in cities located on the east side of Europe. Other studies on the indoor environment of buildings located in Greenland, Beijing and New York cities have also shown that the heating systems of residential buildings in winter generate dry indoor environments where the indoor RH remains below 30% (Kotol et al., 2014; Fan et al., 2017; Quinn and Shaman, 2017). However, it remains to be noted that the recommended RH in the comfort range is 40-70% based on CIBSE Guide A (2015). Clearly, it’s quite necessary to increase indoor humidity in the heating season of these regions.

Portable humidifiers that can be used in residential buildings generally fall into three categories: ultrasonic, cool mist, and warm mist (United States Environmental Protection Agency, 2012). In a cool mist humidifier, air is forced through a water-saturated filter by an in-built ventilator and absorbs the evaporated moisture. The total enthalpy of the air flow is considered as constant in this process (Ghazikhani et al., 2016; Tran Air Conditioning Manual, 2007). Meanwhile, the cool mist humidifier has a 50% of high market penetration (United States Environmental Protection Agency, 2012).

Portable humidifiers humidifying air directly may induce greater impacts than humidification systems installed in ventilation ducts with heat recovery on indoor thermal and humid environment in residential buildings. Feng et al. (2018) studied the impact of the humidification process on the indoor environment in a reference chamber using a portable ultrasonic humidifier generating steam and water droplets. The results indicated that the evaporation of water droplets as a "constant enthalpy process" led to an increase in humidity and a decrease in temperature as shown in Figure 8. During the humidification process, the RH increased gradually from 34% to 90%, while the air temperature decreased by step way.
Figure 8: Variation of relative humidity for sampled points (T: air temperature (°C)) (Feng et al., 2018).

In residential buildings, a portable humidifier is often employed to counteract the effects of heating and keep the indoor RH at a comfortable level. But at the same time, the indoor humidification will conversely have an effect on the heating system. When a cool mist humidifier is used in a heated room with temperature controlled around a comfortable set point by heating systems, the humidification process may result in a reduction of air temperature, which can trigger the room to be reheated. This can be problematic in buildings with floor heating systems that have high thermal inertia.

Li et al. (2022) explored the interaction between the cool mist humidifier and the floor heating system, and compare the effects of different humidification levels on different room temperature set points. The study was conducted in Troyes, France, which belongs to a temperate oceanic climate, and the outdoor temperature was fixed at 5°C based on the local weather data. The obtained results showed that when indoor air temperature is 25°C, humidifying air to over 45% would lead to floor overheating based on ASHRAE Handbook (2016), which gives a limit value of 29°C marked with a black dash dot line in Figure 9.

![Figure 9: Average floor surface temperature with different set points of air temperature and RH (Li et al., 2022).](image)

In order to offset the cooling effect caused by cold mist humidifiers, floor heating systems will supply more hot water to heat the occupied space. As a result, the floor surface temperature increases and so does the power consumption of the floor heating system.

Based on the above findings, it’s possible to use the evaporative cooling effect of a cool mist humidifier for mitigating indoor overheating induced by sun patch.

At present, only one study has been carried out to investigate the interaction between cold mist humidification and floor heating. This is clearly not enough and further research should be carried out in the future in combination with the location of humidifiers, the control of floor heating systems and the exposure of sun patch.

**Predictive controls**

Due to the significant thermal mass in embedded-tube systems and the resulting long response times, overheating often occurs, especially when the heating load is highly variable. For residential buildings, a large amount of south-facing glazing could result in high variability in solar gains, and the indoor relative humidity is generally low with requiring the use of humidifiers during the heating seasons.

In this case, appropriate controls become particularly important. The conventional control strategies suffer from a thermal lag and therefore cannot adapt to varying set points and sudden changes of indoor temperature. Predictive control has been used to compensate for the thermal lag by enabling control actions earlier (Lee et al., 1999; Cho and Zaheer-uddin, 2003; Karlsson and Hagentoft, 2011; Chen, 2002). Chen et al. (2021) established a steady-state model of a radiant floor heating system with variable-flow and applied the PID and MFHS (Model Predictive Control) algorithms to the controller of the supply water temperature. The MFHS controller offered a reduction of approximately 56% in the response time compared with the PID controller.

Besides, Chen et al. (2022) also proposed a thermal response time prediction model by applying the Gaussian regression algorithm. Based on it, an optimal control strategy could achieve a reduction of 41-64% in the response time. Nevertheless, most predictive control models remain nowadays at the theory and simulation stage because of its complexity. However, predictive controllers are usually complex and have no off-the-shelf products. It is based on a non trivial mathematical background that complicates its usage in practice. Široký et al. (2011) analyzed the energy savings that could be achieved through the MFHS implemented in a real building heating system, and found that the potential were between 15% and 28%. Also, the authors highlighted the concerns about the cost and complexity of the MFHS implementation.

Hu et al. (2019) developed a model predictive control for FHS with Trnysys®-Matlab® co-simulation, which could simultaneously consider all the influential variables including weather conditions, occupancy, and dynamic electricity prices to implement automatic and optimal preheating. Candanedo et al. (2011) investigated the application of predictive control techniques in a room with high solar gains by simulations. The results showed that a variable setpoint, which is dynamically modified by a real-time control algorithm according to the weather forecast, is beneficial in improving thermal comfort and reducing energy consumption. Brideau et al. (2020) conducted simulations to compare different types of reactive controllers and predictive controllers for radiant floor heating with high amounts of solar gains in terms of thermal comfort and energy demand. The reactive controllers TRIF and PID performed best in most cases, while predictive controllers performed better than them.
The overheating problems could be avoided or considerably reduced by predictive controllers, however, the complexity of modeling and implementation is a major obstacle to practical application at present. Nevertheless, there are some simple and effective methods, like dynamic fenestration systems - such as automated shading, electrochromic coatings, and others - can prevent or reduce overheating problems by blocking excessive solar radiation, or using the window overhang shading (Candanedo et al., 2011; Benzaama et al., 2016). Besides, at the beginning of a room design, the window size should also be carefully considered to reduce the overheating problem according to both of the thermal comfort and visual comfort (Brideau et al., 2020; Benzaama et al., 2016). The thermal mass of the floor should also be designed combining with the level of solar gain in the room. It is recommended that low thermal mass floors are better with low solar gains and for high solar gains, floors with high mass tend to provide better comfort, as long as the tubes are located near the surface of the floor (Brideau et al., 2020).

Nevertheless, for the people who prefer the sunshine in winter, they don't generally close the curtains, and for the existing buildings, it would be also hard to be retrofitted. Based on this, the methods for easy application should be further explored.

Conclusion

This paper summarizes the relevant researches of floor heating systems, including the inherent factor (thermal mass) and extrinsic factors (solar radiation and cool mist humidification), and the potential solutions for the induced problems. The conclusions are as follows:

The thermal mass in embedded systems has a significant effect on the response time. Many researchers have been working on the structural improvement of radiant slabs. The results show that the thickness and material of the cover and slab, and the water flow velocity are the primary influencing factors on the thermal response of the FHS, but the effects of pipe material and diameter are not significant. The use of heavy slabs and energy storage materials, although making the system slow to respond, also offers longer discharge time to keep the indoor temperature in comfortable range, which has a potential for energy savings.

Solar radiation is an extrinsic factor that cannot be overlooked, especially in the sunny cold days during heating season. For floor heating systems with large thermal inertia and high floor temperature, sun patches are likely to cause the overheating of floor surface. In addition, since there is often a need for humidification during heating season, portable humidifiers humidifying air directly, especially cool mist humidifiers, may induce greater impacts than humidification systems installed in ventilation ducts with heat recovery on indoor thermal and humid environment in residential buildings. The competition between the humidification and the heating process probably leads to the overheating of the floor surface and have an influence on the indoor thermal comfort and the energy consumption of the FHS.

Therefore, cold mist humidification should also be carefully considered as an extrinsic factor.

The overheating problems could be avoided or considerably reduced by predictive controllers, however, the complexity of modeling and implementation is a major obstacle to practical application at present. Adjusting fenestration systems could be an alternative solution, however, for the people who prefer the sunshine in winter, they don't generally close the curtains, and for the existing buildings, it would be also hard to be retrofitted. Based on this, the methods for easy application should be further explored.

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