Results in Engineering 23 (2024) 102544

Contents lists available at ScienceDirect

# Results in Engineering

journal homepage: www.sciencedirect.com/journal/results-in-engineering

Review article

# The development of radiant floor cooling system (RFCS): System type, control strategy, and application

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ARTICLE INFO

*Keywords:*
Radiant floor cooling system
System type
Control strategy
Application
Anti-condensation

ABSTRACT

The utilization of radiant floor systems is one effective method to address the increasing cooling demand. The radiant floor cooling system (RFCS) has self-regulating capabilities, which benefit grid stability and the use of renewable energy. The application performance of RFCS is based on system design and intelligent control, as systems with high thermal inertia make it difficult to provide ideal indoor response effects. Therefore, this review aims to summarize the current development status of RFCSs and evaluate future development directions based on relevant research trends. A comprehensive overview of the radiant floor structure and the composition of RFCS were provided. The type of radiant floor structures can bring greater possibilities for the application of RFCSs. Then, system control and evaluation are analyzed, with research on anti-condensation of radiant floors mainly focused on system and environmental control. Based on application status of the RFCS, the impact of various factors is discussed, including condensation risks, and climate change. Resistance to disturbances not only requires implementing control measures but also integrating with the building environment. There is still great potential for the hardware design and multi-directional integration of RFCS. The results of this review help relevant researchers gain a comprehensive understanding of the current development status and prospects of RFCS contributing to the decarbonization of the construction industry.

## 1. Introduction

In recent years, the construction industry has gradually veered off track to meet the Paris targets, with construction operations accounting for around 30 % of global energy sector emissions in 2022 [1]. To combat this, the building industry needs to promote zero-carbon, resource-efficient, and resilient buildings [2]. Radiant cooling systems can integrate into zero-energy or green buildings while providing equivalent or superior comfort compared to all-air systems [3–5]. According to the types of radiant cooling terminal, the system can be divided into radiant floor system, radiant wall system, and radiant ceiling system. Among these, radiant floor cooling system (RFCS) has been extensively utilized in engineering for efficient cooling [6,7].

Radiant floor cooling system is an evolution of radiant heating systems. Initially, people used hot gases or water to raise indoor temperature by heating the floors, walls, and kang. The success of this heating method gained the interest of researchers, leading to the development of radiant floor heating systems and the subsequent popularity of this system. With the demand for indoor thermal comfort and energy-saving performance improved, researchers began to explore radiant cooling in the 1930s [8]. These systems have been successfully implemented in buildings, marking a new chapter in radiant floor cooling. The radiant floor system has advantages in indoor cooling, despite their low heat transfer coefficient [9]. Energy saving is one of the advantages of RFCS. The larger heat exchange area of the radiant floor allows it to regulate the indoor environment under smaller temperature differences between radiant floor temperature and air temperature. High temperature cooling water can be obtained through natural cold

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https://doi.org/10.1016/j.rineng.2024.102544
Received 2 May 2024; Received in revised form 24 June 2024; Accepted 9 July 2024
Available online 14 July 2024

sources in order to reduce the use of primary energy [10,11].

As a low-exergy technology, RFCS can maximize the coefficient of performance in the built environment by reducing exergy demand and increasing exergy efficiency [12,13]. To prevent condensation on the radiating surface, the radiant floor surface temperature cannot exceed the indoor dew point temperature [14]. While this limits cooling ability of the radiant floor, RFCS could transfer indoor cooling loads through the thermal mass of the building, reducing peak loads [15,16]. However, high thermal mass will result in long system response times [17,18], which is not conducive to the transient control of indoor thermal environment. Furthermore, inefficient utilization of energy stored within buildings can lead to energy wastage [19,20]. This problem can be addressed by implementing flexible control strategies and suitable system types [21,22]. The operating performance of RFCS is affected by the climate parameters and building types. Specifically, the system can bear more indoor cooling load in dry climates compared to wet ones [23]. To improve the adaptability of RFCS in different climate zones, coupling ventilation system or dehumidification system is necessary to cope with indoor latent load or auxiliary cooling [24–26]. The energy consumption of the integrated system is inversely proportional to the sensible load that the ventilation system bears [27]. Ultimately, the operational performance and energy efficiency of the hybrid system are significantly affected by the system design and control strategy.

Previous reviews have extensively covered various aspects of the RFCS, as summarized in Fig. 1. They mainly focus on "system design" [26,28,29], "thermal comfort analysis" [3,30,31], "system control" [32,33], "economic analysis" [34,35], "system application" [36,37], "heat transfer and model" [38] and "cooling capacity" [10]. Although this review intersects with previously discussed topics in the literature, they have primarily focused on the entire radiant system. According to current literature, there are significant differences between various types of radiation terminals, including condensation risk, cooling efficiency, and energy-saving benefits. The theories and application guidelines related to different types of radiation systems are not universally applicable. Although there has been independent research on the system, control, and parameter analysis of radiant floor, there is a lack of organization and exploration of various technological developments. Therefore, it is necessary to make further efforts to review the opportunities and challenges of RFCS.

Fig. 2 shows the sustainable development methods for implementing the system. Based on this, this article first discusses different types of systems, including radiant floor systems and ventilation systems, and studies the advantages and limitations of integrated systems. Then, the focus was on introducing the relevant theoretical knowledge and design criteria of RFCS in control. Combined with climate and architectural characteristics to reduce fluctuations caused by uncertain factors, the application challenges were analyzed. Finally, a conclusion was drawn and the future development of RFCS was discussed to highlight its competitiveness in ultra-low energy buildings.

## 2. System type

The radiant floor will be integrated into the building, and the purpose of system design is to combine subjective and objective conditions to initially reduce system energy consumption and ensure thermal comfort. Reasonable design of different subsystems is crucial for the response rate and control effectiveness of subsequent systems. In this section, a comprehensive introduction was given to three parts: radiant floor, ventilation systems, and cold sources, and the latest research progress in system design was summarized.

### 2.1. Radiant floor structures and cold sources

#### 2.1.1. Radiant floor structures

The hydraulic radiant floor structure mainly consists of floor covering (Tiles, marble, and concrete, etc.), weight-bearing (cement screed, anhydrite screed, asphalt screed, and timber), and thermal diffusion layer (aluminum heat diffusion devices, and Steel heat diffusion devices), insulating insulation (Polystyrene foam and foamed concrete, etc.), acoustic insulation (if present), structural bearing, contraction joints, expansion joints (movement joints), and construction joints composition [39]. Based on the thermal response time, radiant floors can be classified into two categories: medium-response radiant floors and slow-response radiant floors [18], as illustrated in Fig. 3. The main difference between these two types lies in the placement of the buried pipe and the presence of insulation. The most common type of

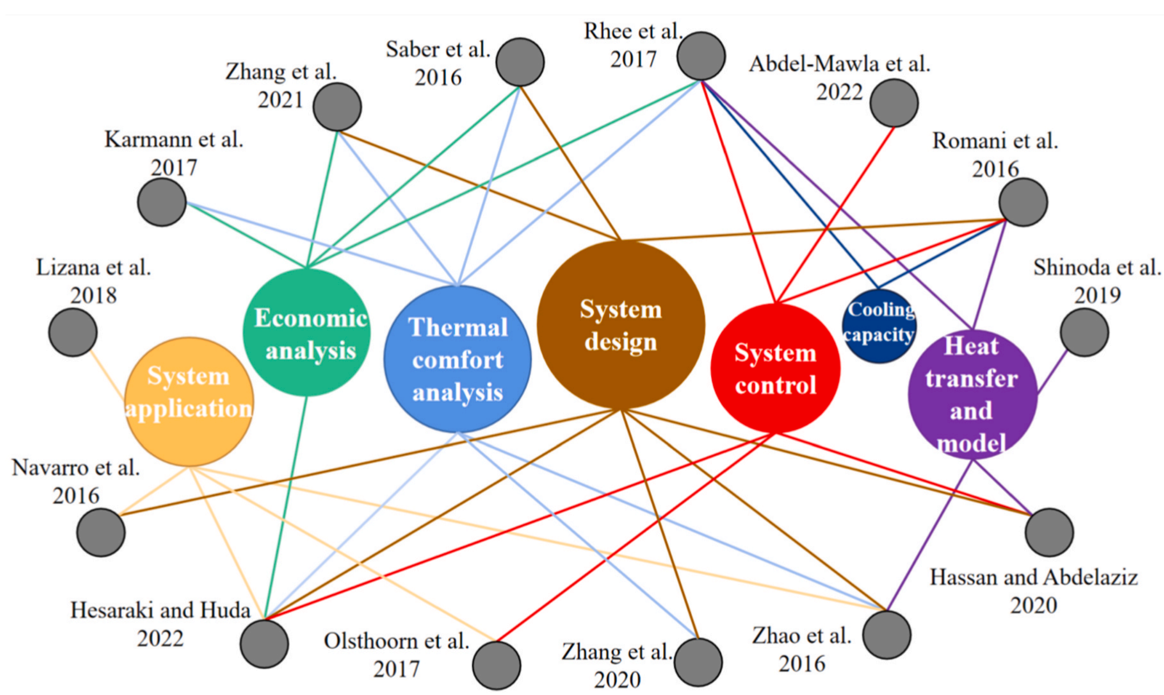



**Fig. 1.** The research points of RFCS mentioned in the previous review literature.

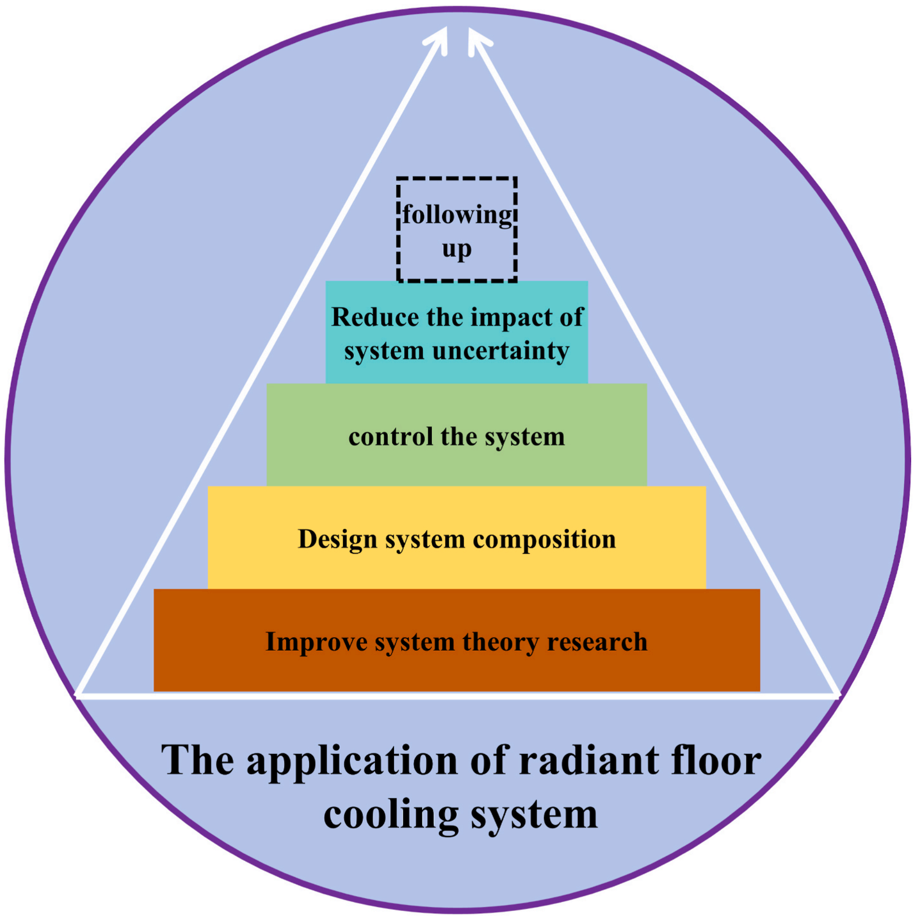



**Fig. 2.** The sustainable development methods for implementing the system.

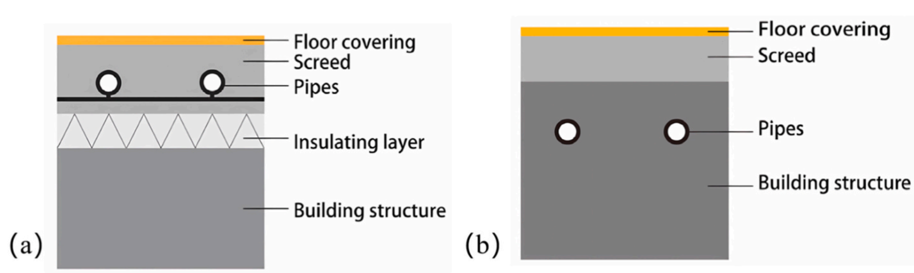



**Fig. 3.** Structural representation of typical radiant floors [18]: (a) Medium-response radiant floor and (b) Slow-response radiant floor.

radiant floor is the concrete core radiant floor, in which pipes are embedded within the concrete layer [40]. Pipes pass through the concrete slabs to deliver cooling to the interior and store in concrete slab.

The thermal capacity of the system is primarily determined by the thickness of the surface layer in which the pipes are embedded [41]. A slow-response radiant floor possesses a larger heat storage capacity that can minimize the impact of indoor load and external climate on the indoor thermal environment. When turned on and off, charging and discharging phenomena occur. Medium-response radiant floor exhibits good insulation and has lower thermal mass, leading to lower thermal inertia and faster reaction times for floor. When the step change in control of the system is applied as input, it takes 9.7–18.8 h for the surface temperature of the slow-response radiant floor system to reach 95 % of the difference between its final and initial values, while the medium-response takes 2.3–8.7 h. Due to the reduction in the cooling of the building envelope, Medium-response radiant systems are more suitable for retrofitting existing buildings than slow-response radiant floor. The cooling capacity of radiant floor demonstrates similar tends across different response times [42]. Most simulation studies presume steady-state conditions.

According to the methods of construction and installation of hydraulic radiant floor, the hydraulic radiant floor can be categorized into two types: wet construction (also known as heavyweight system) and dry construction (also known as lightweight system) [43], as shown in Fig. 4. In wet construction, pipes are covered with cement or mortar and embedded directly into the building structure. The temperature distribution on the surface of a floor constructed using the wet method is more uniform [44]. However, with advancements in technology, dry construction has become more popular. The pipes in dry construction are placed on a heat insulation layer, making them easy to install and maintain. They are particularly useful for secondary air conditioning system transformations [45,46]. Dry construction radiant floor has smaller thermal resistance, which has prompted most research to focus on their dynamic performance. Thomas et al. [47] established a finite

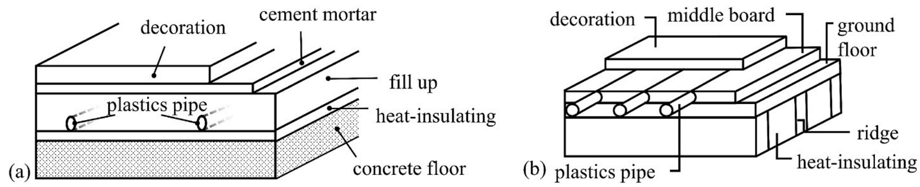



**Fig. 4.** Two pavement methods of radiant floor [45]: (a) Wet construction and (b) Dry construction.

element numerical model of the dry construction radiant floor and tested the accuracy of the model through experiments. It was found that the energy-saving advantage of light floor in steady-state mode was not significant compared to classical radiant floor. Zhao et al. [22] compared the dynamic behavior of heavyweight system and lightweight system and found that heavyweight floor when stably operated in high-intensity solar radiation environments, exhibited better performance than lightweight floors, with a cooling capacity 3.06–5.73 W/m$^2$ higher than that of low thermal capacity floors. They also proposed a method for predicting peak cooling loads.

Active hollow core slabs developed and popular in Europe that utilize air as a heat transfer medium are also used in building cooling [48]. Fig. 5 displayed the basic structure of active hollow core slabs, which employ fans to circulate air through hollow cores, enabling a cycle of charging, storage, and discharging. Underfloor ventilation system serves two primary functions: cooling the air in the pipe using the low-temperature floor, and providing radiative cooling to the room by blowing cold air [48,49]. However, due to the limited air-to-floor contact area, it is necessary to improve the composition of the radiant floor to enhance its cold storage capacity and make up for the insufficient cooling supply. Active hollow core slabs necessitate sufficient ventilation space in the floor structure. Hydraulic radiant floors are more widely used and have unique advantages than active hollow core slabs. Therefore, the review pays more attention to the water medium radiant floor.

Based on the existing research, the radiant floor structure and material aspects have been optimized, as presented in Table 1. The optimization goals primarily focus on the response capacity and cold storage capacity [43,50]. An uneven temperature on the surface of the radiant floor can lead to thermal discomfort and localized condensation. By incorporating a steel base into the radiant floor, the uneven surface temperature can be reduced, subsequently affecting the heat storage capacity. Despite the potential for longer response times, energy storage can enhance the cooling capacity of the floor and reduce peak load [51,52]. From the table, it can be seen that using phase change materials to improve the cold storage capacity of radiant floors has become a research hotspot. The design of radiant floor should not only consider performance but also factors such as installation flexibility and cost.

### 2.1.2. *Cold sources*

The indoor environmental parameters and indoor thermal comfort affect the water supply temperature of the system, which is generally between 16 and 22 °C [61]. Sometimes lower temperatures have been chosen in certain studies [62]. Thus, RFCS offers more flexibility in selecting the cold source. Typically, traditional air conditioning systems rely on chillers to produce cold water at around 7 °C to meet air cooling and dehumidification requirements. However, when using a chiller as the cold source of radiant floor system, it is necessary to mix high-temperature water or use heat exchanger to adjust the supply water temperature [63]. To obtain high-temperature cooling water, alternative cold sources such as heat pumps [64,65], solar cooling systems [66], evaporative cooling systems [67,68], and direct-ground cooling systems [12] are preferred. These advanced technologies have gained popularity due to their applicability to radiant floor systems.

Heat pumps utilize a small amount of high-level energy to transfer heat from a low-level heat source to a high-level heat source, with a high coefficient of performance (COP). The incorporation of radiant floor system can improve the COP of heat pumps and reduce the demand for primary energy. Under the same power generation source, the radiant floor systems using heat pumps have shown promise as energy-saving systems that reduce carbon emissions and exergy loss [69]. The COP of the geothermal heat pump and radiant floor system can achieve 5.29, effectively fulfilling the cooling demand of the building [70].

However, the radiant floor systems have strong adaptability to direct cooling from natural cold sources and the hybrid systems are more environmentally-friendly and energy-efficient [63,71]. The use of natural cold sources comes with strict outdoor requirements. The temperature of water through the direct-ground cooling system and evaporative cooling system can fluctuate based on seasonal weather and other operational factors [72]. Improper design of cooling requirements may result in soil energy imbalance or indoor overheating [73,74]. Therefore, natural cold sources are commonly used as an auxiliary source of the system. In fact, due to radiant floor energy storage, natural cold sources can also provide considerable hours of acceptable thermal comfort for the room in extreme climates [68,75]. Fig. 6 displays the schematic diagram of the RFCS with direct-ground cooling system employed in an office building [11,76]. The use of geothermal heat exchangers as a cold source provided good thermal comfort without requiring additional steam compression cycles [12]. Hybrid renewable

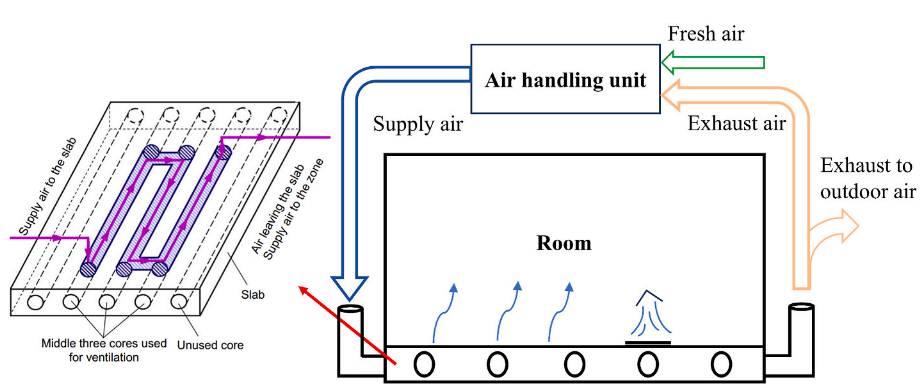
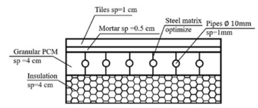
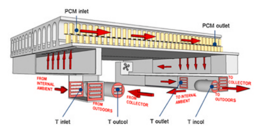
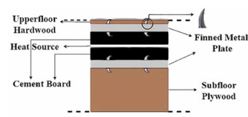
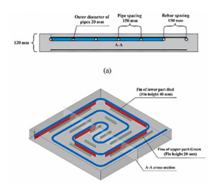
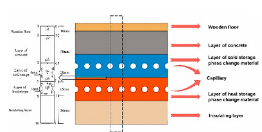
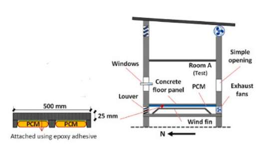
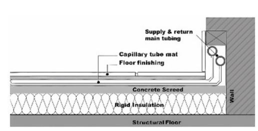
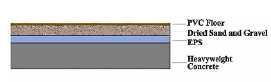
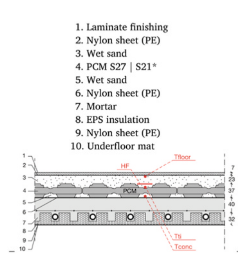



**Fig. 5.** Structure of active hollow core slabs [48].

**Table 1**
Summary of research on radiant floor structure.

| Reference | Year | Description | Illustration | Findings |
|---|---|---|---|---|
| [52] | 2011 | The steel matrix was added into the PCM layer. |  | The developed radiant floor improves the uniformity of phase change material temperature in the floor, reduces the response time of the floor, and can achieve indoor cooling and heating. |
| [53] | 2015 | PCM material was added to the hollows of the hollow floor |  | Due to the energy loss of prefabricated concrete slabs during the summer cold storage period, their discharge efficiency is low in summer, and reasonable control is needed to optimize system energy consumption. |
| [54] | 2020 | The floor was fitted with metal plates with nails. |  | Compared with concrete-based radiation panels, the new type of radiation panel reduces operating costs, greenhouse gas emissions, and energy consumption, and improves system response speed. |
| [55] | 2021 | The aluminum alloy fins were added between two pipes. |  | Finned concrete radiant floor reduces temperature differences along the thickness direction. The heat storage performance of system is influenced by the height and material of the fins, but not by the thickness of the fins. |
| [56] | 2021 | Radiant floor system based on double-layer capillary phase change heat storage |  | The radiation system can meet night energy storage and daytime discharge, and the floor surface temperature at different water supply temperatures was similar. |
| [57,58] | 2022 | Integrate PCM and reserve under-floor space for forced ventilation storage at night |  | The thickness of the PCMs in the proposed system affects the duration of the cooling effect. In hot and humid conditions, a 6-cm thickness of phase change material is optimal. |
| [46] | 2022 | Tube mats are used to replace the original plastic or metal pipes |  | Tube mats are used to reduce response time and provide more flexible design and installation, but smaller pipe diameters may cause blockage |
| [59] | 2022 | Double-layer PCM |  | The total thickness of the double-layer PCM layer in the radiant floor affects its heat storage capacity. After parameter optimization, the indoor thermal comfort rate of PCM Coupling Room is as high as 81.58 %. |
| [60] | 2022 | PCM (Hydrated salts ) is installed above the mortar layer, and polyethylene pipe located above EPS insulation. |  | The weather forecast can alleviate supercooling and overheating, and it is advisable to use a 6-h forecast time in summer. |

energy systems can help alleviate energy intermittency issues [77]. The COP of a radiant floor system that integrates ground temperature, water evaporation, and sky radiation can reach 19 during operation [78]. City tap water can also be used as a source of cooling for radiant floor systems in residential buildings [79].

### 2.2. Combination with air system

The air system is crucial for the radiant floor system to operate effectively in hot and humid environments. Compared to the two, hybrid systems composed of both can combine their respective advantages and compensate for their shortcomings. The following provides an overview of different hybrid system studies and types of ventilation systems are introduced below.

#### 2.2.1. System characteristic

Radiant floor system is inefficient as a standalone method in hot and humid climates due to the risk of condensation on the floor surface. To improve cooling capability of system, natural night ventilation cooling is commonly employed as an auxiliary cooling method in conjunction with radiant floor systems [65,80]. However, the enhancements provided by natural ventilation alone are insufficient. It is common to integrate them

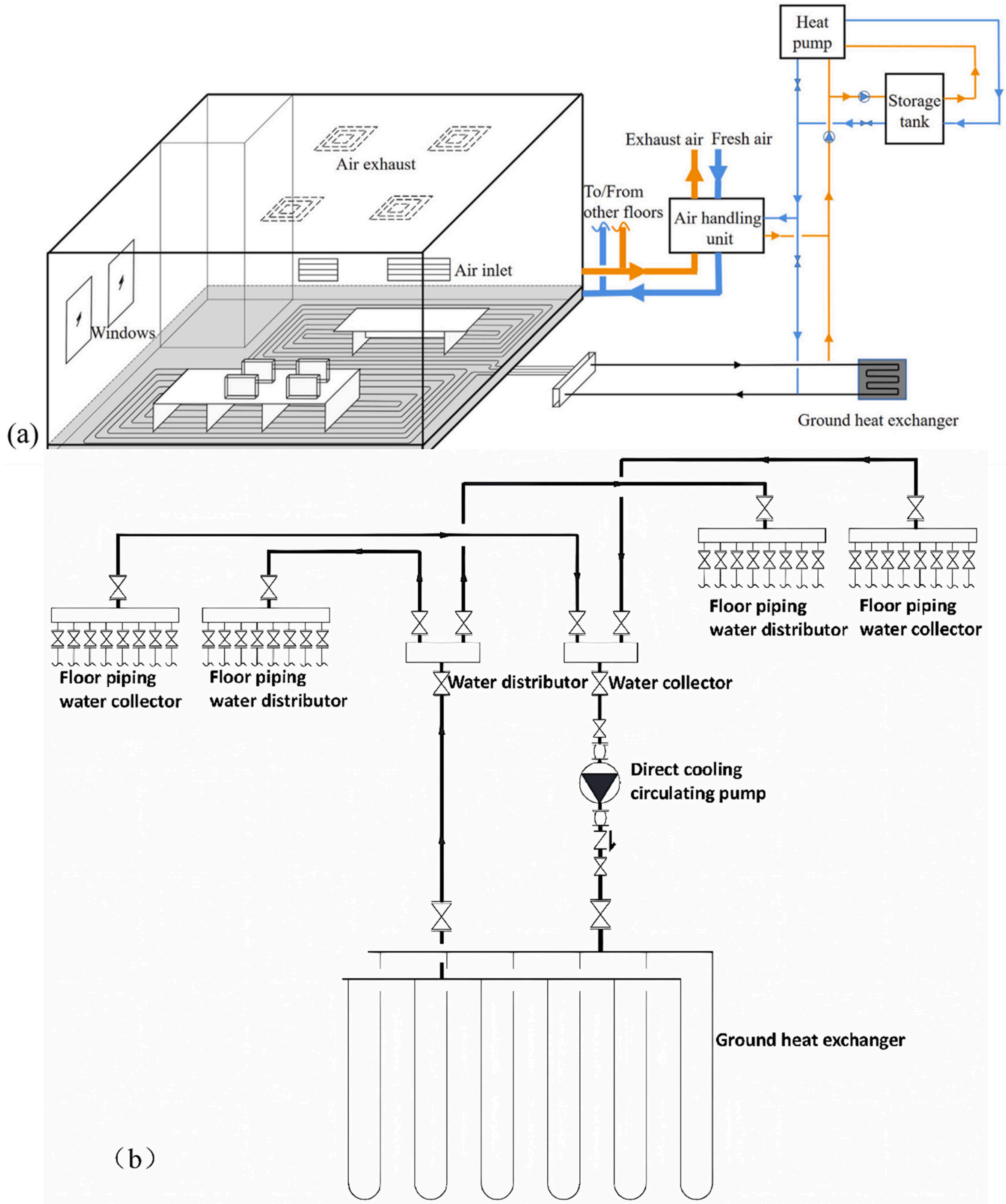



**Fig. 6.** The cold source type of the radiant floor system. (a) Schematic diagram of the direct-ground cooling system with RFCS [11], and (b) Schematic drawing of direct-ground cold source system in summer [76].

with convection systems in buildings (see Fig. 7), such as cooling systems (dry coil units, chilled beams) [81,82], dehumidification systems (dehumidifiers) [83], and cooling and dehumidification (wet coil units, air handler units (AHU), variable air volume (VAV)) [50,84,85]. These integrated convection systems offer a wider operating range and quick response to changes in the indoor environment while controlling indoor humidity. The optimal cooling proportion of radiant floor system in integrated system with large spaces is 0.76–0.77 [86].

Ventilation systems help to enhance the cooling capacity of integrated systems and improve the response capabilities. Cooling and dehumidification systems are the most widely used to treat outdoor fresh air directly. Zarrella et al. [25] conducted a comprehensive study to compare five types of RFCSs used in residential buildings. The study revealed that, when indoor conditions were maintained constant, fan coil and mechanical ventilation provided better thermal comfort than the dehumidification system. Moreover, mechanical ventilation can improve indoor air quality. Radiant floor system integrated with separate cooling and dehumidification systems allows for a larger range of temperature fluctuations in the radiation floor. Gu et al. [64] investigated a hybrid radiant floor system that integrated a fan coil unit and an outdoor fresh air dehumidifier. Their findings indicate that the fan coil assists the radiant floor system in providing cooling and adjusting the

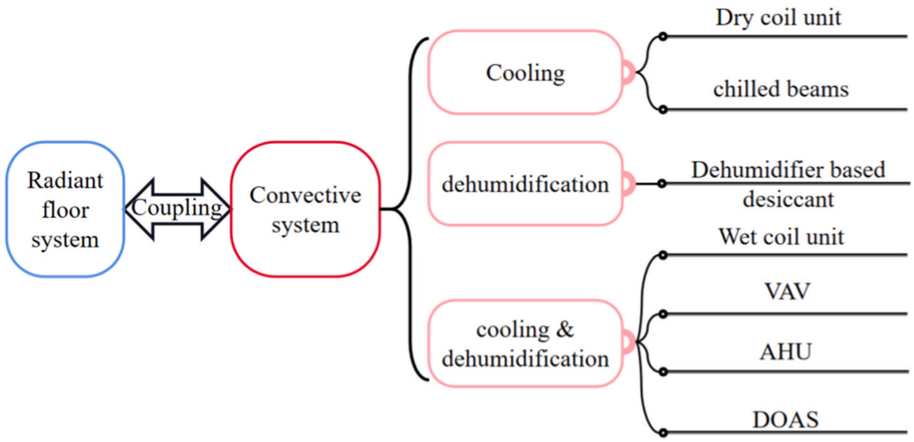



**Fig. 7.** Classification of integrated convective systems for radiant floor cooling systems.

environment in different areas, while the outdoor fresh air dehumidifier controls indoor air humidity to maintain air quality. Overall, a separate fan coil in hybrid system can not only achieve satisfactory indoor thermal comfort but also achieve multi-zone control. On the other hand, dehumidification systems which integrate solar heat and indoor air heat recovery reduce the moisture content in the air, making them suitable for room with high latent heat loads or where maintaining low indoor humidity levels is necessary [87]. If only considering the removal of the typical indoor latent load, the exergy efficiency of the condensing dehumidification system can be 3 to 4 times higher than that of the desiccant wheel dehumidification system [88].

### 2.2.2. *Ventilation types*

Anti-condensation control on radiant floor surfaces and maintaining indoor air quality are essential responsibilities of the ventilation system. Integrated systems help to maximize the efficiency of the cooling system [83] and make the radiant floor system adaptable to different climates [23,65]. When radiant floor systems have large thermal mass, it can improve the response time of hybrid system. Compared to traditional convective air conditioning, the combination of a ventilation system and a radiant floor system reduces the cooling energy required for ventilation. This is due to the lower air mass flow rate, which results in reduced ventilation system noise and a smaller ventilation pipeline volume [31]. Fig. 8 shows a system diagram of RFCS with different ventilation types. The ventilation methods for RFCS include displacement ventilation [86], mixing ventilation [89], personalized ventilation [90], and underfloor ventilation [91,92].

Displacement ventilation offers strong sewage discharge capability and has low operating costs. The combination of radiant floor system and displacement ventilation system has a direct and positive effect on the indoor thermal environment, and the presence of radiant floors aids heat transfer [93]. The ventilation vents near the floor effectively isolate the indoor humid air from the floor and reduce the risk of condensation on radiant surfaces. Two potential issues arise: the effect of supply air temperature on the heat transfer of the radiant floor and the distribution of indoor temperature gradients when vents close to the floor. However,

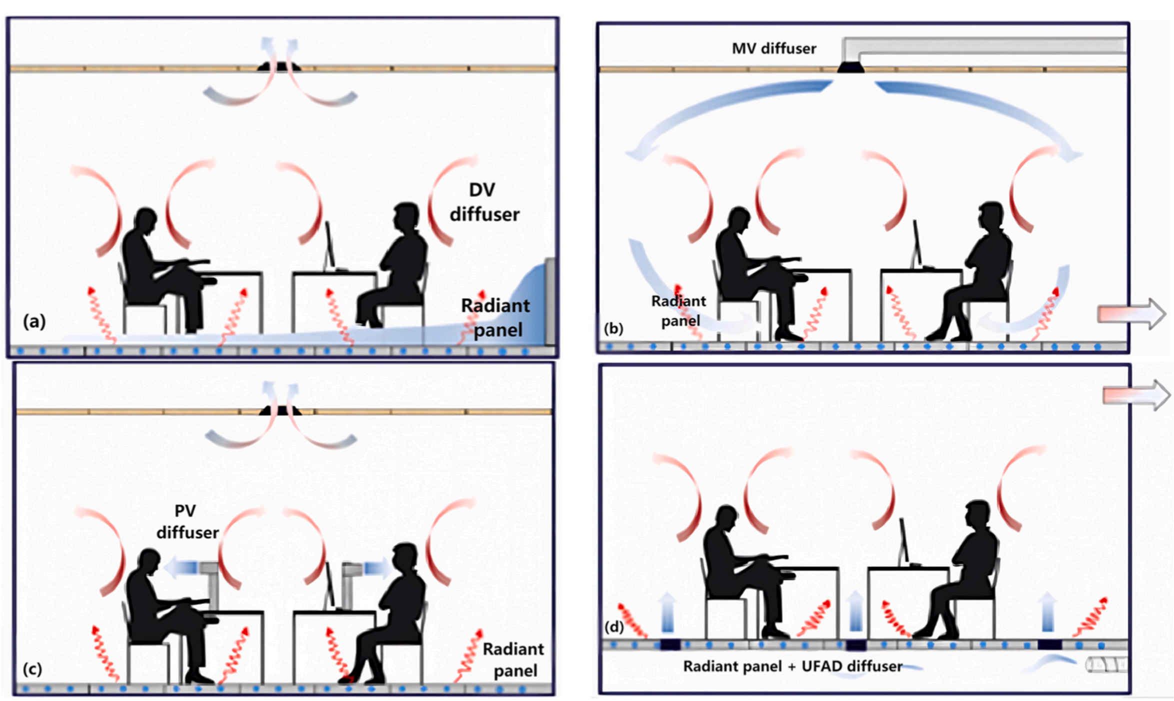



**Fig. 8.** Schematic diagram of radiant floor system and different ventilation methods [31]: (a) displacement ventilation (DV) + radiant panel, (b) mixing ventilation (MV) + radiant panel, (c) personalized ventilation (PV) + radiant panel, and (d) underfloor ventilation (UFAD) + radiant panel.

it does not cause thermal discomfort on the feet/calves [94,95]. Schellen et al. [96] found that the vertical temperature gradients in the room with radiant floor system combined displacement ventilation could up to 4 °C and provides better comfortable conditions than combined mixing ventilation. In high-space buildings, the combination of displacement ventilation and radiant floor system allows for thermal comfort adjustment solely in the occupied space [62]. The radiant floor system integrated displacement ventilation system has been successfully applied to the departure hall and check-in hall of Terminal 3 of Xi'an Xianyang International Airport. This system provides good thermal comfort during cooling periods, as well as a 34 % reduction in energy consumption compared to traditional jet ventilation systems [83].

Except for displacement ventilation, other ventilation types combined with radiant floor systems have received less research attention [31]. Mixing ventilation is commonly used in traditional air conditioning and maintains lower vertical air temperature differences in the room [89,97]. The better ventilation results can be accomplished when the supply air temperature equals or is lower than the room temperature for mixing ventilation [98]. Mixing ventilation mainly dilutes the air to maintain indoor air quality, but it is not efficient in removing pollutants from dead spaces in the room under cooling conditions. The combination of mixing ventilation with a radiant floor system could elevate the risk of airborne pollutant transmission due to reduced ventilation volume. In fact, mixed ventilation is more typical in radiant floor heating systems than in RFCS [31].

Personalized ventilation systems supply fresh air directly to the personnel breathing zone and are linked to indoor facilities [99]. Due to the need for duct design in personalized ventilation systems, which can affect the layout and aesthetics of the room, ductless personalized ventilation systems have been developed. Ductless personalized ventilation systems intake fresh air distributed in the upper zone near the floor and transports it to the breathing area of each user [100]. The application of ductless personalized ventilation systems requires the cleanliness of the air in the upper zone near the floor, often used with displacement ventilation. Liu et al. [101] reported that combining ductless personalized ventilation with radiant floor and displacement ventilation systems can create an improved local thermal environment and pollutant removal effect. The ductless personalized ventilation reduces the vertical air temperature difference between 1.1 m level and 0.1 m level by 1.79 °C. It is recommended a flow rate of 5 L/s and an air intake height of 0.1 m for ductless personalized ventilation.

Like personalized ventilation systems, underfloor ventilation systems also require available underfloor space. The heat transfer performance of the radiant floor is affected by wind speed and underfloor air supply temperature [102]. Fernández Hernández et al. [103] have developed a novel composite floor air distribution system (refer to Fig. 9) and found that the interaction between underfloor ventilation system and the radiant floor system is not immediately evident. The composite system not only enhances chiller efficiency and augments the cooling capacity of the radiant floor system but also prevents condensation on the radiant surface. The underfloor ventilation modality is suited for public buildings or residential buildings where the diffusion area is free of pollutants.

### 2.3. Combination with radiant terminals

The cooling capacity of a radiant floor system is the key point of its application, the energy-saving potential of a radiant system increases as it takes on a greater indoor load. Radiant floor system can be used with other radiant terminals within a building to enhance cooling capacity [72]. There are three main methods of combining radiant terminals (Fig. 10): radiant floor + radiant ceiling [104,105], radiant floor + radiant wall [6], and radiant floor + radiant wall + radiant ceiling [51]. Due to the dominant role of heat transfer in the active chilled beam systems, they are not discussed in this chapter due to the dominant role of convective heat transfer [3]. The most common combination is the use of radiant floor and radiant ceiling which is prevalent in thermally activated buildings. These buildings use non-insulated pipes embedded in the floor slab to evenly distribute heat upwards and downwards, being referred to as radiant floor/ceiling cooling system [105]. The asymmetric thermal radiation can be reduced by a symmetrical configuration of the radiation surface [106]. Furthermore, the combination of radiant walls and radiant floor can provide uniform thermal comfort [107]. Carli et al. [6] conducted a study on an office building in Austria that used a combination of radiant walls and radiant floor and found that the operating temperature of an office was below 26 °C during the cooling period. Finally, the integration of phase change materials on different radiant surfaces can create cool surface effects and provide a new avenue for improving indoor thermal comfort [51].

To improve the efficiency of radiant cooling systems while ensuring indoor thermal comfort, integrating various radiant surfaces is effective. However, there are still certain issues that require attention. The primary area of concern is the cooling and heating capabilities of the radiant terminals and distribution of the indoor load. Tian et al. [61] conducted experiments in Canadian climate conditions to analyze the thermal comfort and thermal environment of radiant floor/ceiling cooling system. The results indicate that 67 % of the subjects felt overcooling in summer due to inappropriate system design. Another issue to be considered is the response time of the system, which can vary significantly among different types of radiant systems, posing challenges in controlling the system [18]. Finally, condensation risk on radiation surfaces can also be problematic. To combat this issue,

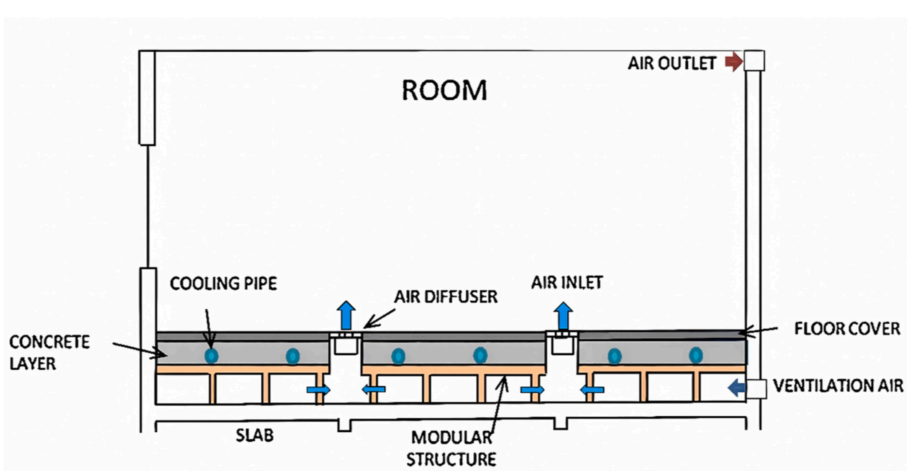



**Fig. 9.** Radiant cooling floor integrated with an underfloor air distribution system [103].

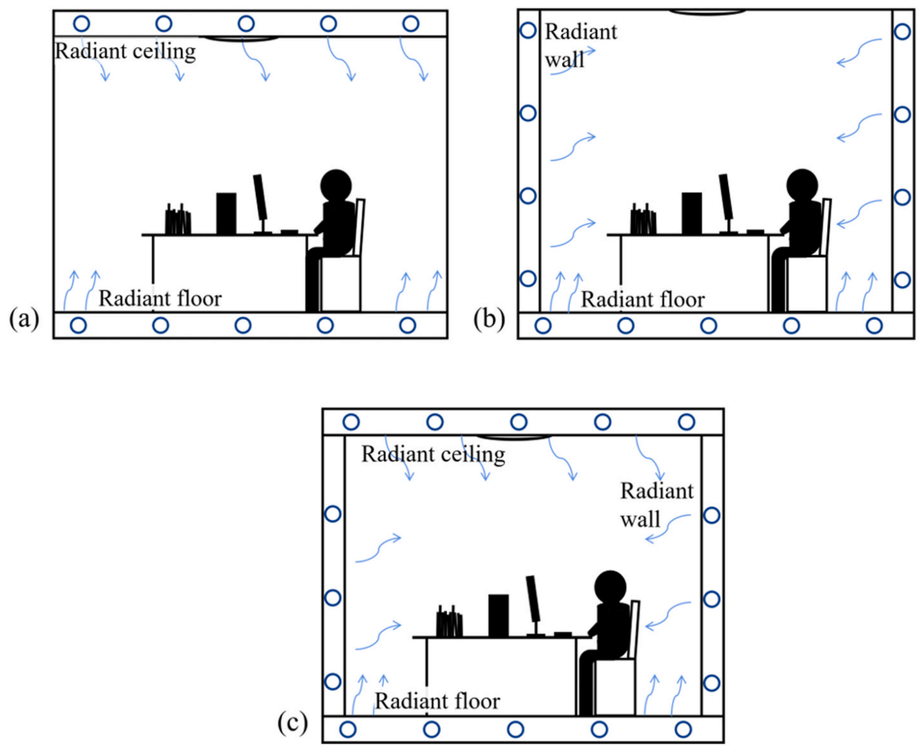



**Fig. 10.** Composite diagram of radiant floor and other radiant terminals: (a) Radiant floor + radiant ceiling, (b) Radiant floor + radiant wall, and (c) Radiant floor + radiant wall + radiant ceiling.

anti-condensation measures should be comprehensively designed and implemented across each surface [108].

## 3. Control strategies

### 3.1. Current research status

The control issues of air conditioning include nonlinear dynamic behavior of the system, variable and uncertain disturbances, time-varying set points, passenger-centered ventilation nature, integration of modern technologies, and energy efficiency [109,110]. Radiant floor systems require more complex control methods due to the small temperature difference between the indoor temperature set point and the cold source, as well as the high thermal mass of radiant surfaces.

The traditional control strategies are effective [111], but advanced control strategies have been shown the potential to significantly reduce energy consumption [81]. The primary aim of control strategy is to achieve better thermal comfort and energy performance by regulating supply water temperature, supply water flow rate, supply air temperature, and supply air flow rate [41]. Indoor control parameters include indoor air temperature, operative temperature, predicted mean vote (PMV), and indoor dew point temperature. Traditional control strategies make control decisions based on identifying changes in indoor parameters, which may pose a risk of indoor overheating [88]. To reduce control delays, control actions are predicted in advance based on disturbances. Nonetheless, the mutual influence between temperature and humidity control can lead to increased control error [27,112]. As a result, various control strategies have been studied for RFCS to ensure both thermal comfort and cost-effectiveness. Table 2 provides an overview of the current state of research on control strategies for the RFCS. About two-thirds of the research have been conducted via simulation, as it makes simulation methods more convenient and comprehensive for conducting systematic multi-factor analysis. While experimental evaluations have demonstrated the efficacy of complex control strategies, comparatively little research has been conducted on the practical operation and management of these strategies.

### 3.2. Control method

According to the control classification of the heating, ventilation, air-conditioning and cooling system, the control strategy of the RFCS can also be divided into four types [109]: conventional control, rule-based control, hybrid, soft-computing control, and advanced control.

#### 3.2.1. Conventional control

Conventional control strategies for indoor temperature control include manual control, ON/OFF control, feedback control, and PID control. The traditional ON/OFF control is a basic and uncomplicated control that does not require intricate parameter settings. The frequent switching of system water pumps can be prevented by applying a dead zone control at the set point. At the same time, energy consumption will be reduced [21,105,115]. However, the system responds to indoor environments through on/off control, which can lead to temperature lag under high thermal inertia and variable climate conditions [65]. Many current buildings have added digital control, and PID control is mainly based on feedback closed loop, it is mainly used in modern buildings with variable frequency motors [109]. Employing PID control, floor surface temperature can be precisely regulated by controlling the indoor air temperature with an accuracy of $\pm$ 0.05 °C [128]. Conventional control strategies are commonly adopted in real building environments due to their cost-effectiveness and simplicity. However, RFCSs exhibit nonlinearity and slow response characteristics, and improper selection of the controller parameters could result in its unstable output [129]. Engineers need to invest significant time and knowledge in tuning and calibrating the PID parameters (proportional, integral, and derivative). Reliable and sensitive algorithms are needed to assist in selecting control parameters for adaptive changes in system parameters.

#### 3.2.2. Rule-based control

Rule-based control is an interesting optimization method, including

**Table 2**
A summary of the literature on the control strategies applied to the RFCS.

| Reference | Year | Location/ Building type | Method | System | Control strategies | Main findings |
|---|---|---|---|---|---|---|
| [105] | 2007 | Germany, Italy/ Office building | Simulation | VS + RFC | Variable water supply temperature control, Dead zone control | Controlling water supply temperature based on outdoor temperature conditions ensures satisfactory indoor conditions while minimizing energy use for cooling, pump. The temperature dead zone should not be greater than 2 K. |
| [24] | 2008 | Korea/Residence | Experiment, Simulation | DOAS + RF | Outdoor reset control with indoor temperature feedback | The control strategy improves the ability of the composite system to cope with internal load changes. |
| [113] | 2008 | Switzerland/ Office | Simulation | VS + RF | Unknown but bounded control | Unknown but bounded control method can manage unforeseen daily variations and room-to-room fluctuations in heat gain, allowing for automatic switching of the cooling/heating modes. |
| [114] | 2009 | Switzerland/ Laboratory | Simulation, Experiment | RFC | Pulse width modulation control | The PWM control can reduce the power consumption of the pump by more than 50 %, and fit into newly developed TABS control solutions. |
| [63] | 2011 | Central Europe/ Office Building | Simulation | RF | Pulse width modulation, Variable water supply temperature control, Night operation | The pulse width modulation control can reduce the power requirements of the water-circulating pump by more than 50 % compared to continuous operation. |
| [80] | 2014 | Korea/Residence | Simulation | VS + RF | ON/OFF control, Feedback control | Proper operation of outdoor air-cooling strategy can reduce the cooling energy consumption of more than 20 %. |
| [115] | 2014 | Belgium/Office building | Simulation | AHU + RF | Peak shaving strategy, Intermittent ON/ OFF control, night operation, Variable water supply temperature control | The 6 % reduction in primary energy consumption at night operations which was the best and the TABS allowed for significant load control. |
| [116] | 2014 | India/Office building | Experiment | DOAS + RF | Variable water supply temperature control, Intermittent control | The simplest and most robust strategy is to control manifold valves based on a fixed return water temperature. |
| [13] | 2015 | United States/ Office building | Simulation | DOAS + RFC | Model predictive control, Feedback control | The low-lift cooling system saves 24 % more electricity than the variable air volume system when using model predictive control. |
| [117] | 2015 | India/ Commercial building | Simulation | FCS/ DOAS + RFC | Intermittent ON/OFF control | The DOAS-integrated radiation system outperforms the fan coil unit-integrated system. Compared to original scheduled operation, The radiant system can save more than 10 % of operating energy when turned off 4 h before. |
| [111] | 2015 | Denmark/Office building | Simulation | VS + RF | Intermittent ON/OFF control | Compared with room temperature feedback control, schedule intermittent control has better thermal comfort. |
| [112] | 2016 | United States/ Office building | Simulation | AHU + RF | Proportional integral control, Model predictive control | Predictive control enables system precooling, load transfer, and can result in a 10 % reduction in energy consumption. The coordinated control of the system saves about 2 % more energy than that of RFCS. |
| [75] | 2017 | United States/ Office Building | Simulation | VS + RFC | Intermittent control, Feedback control | Compared with conventional start-stop control, this method can reduce power cost and energy consumption by 40 % or 35 % while maintaining indoor thermal comfort. |
| [118] | 2018 | United States/ Laboratory | Experiment | RF | Variable water supply temperature, regional flow control | The air temperature replaces the operative temperature to control the radiation system. Ceiling fans will help reduce any excessive delamination and provide thermal comfort at higher zone temperatures. |
| [119] | 2018 | United States/ Laboratory | Experiment, Simulation | VS + RF | Pulsed flow control method, Intermittent control, Variable water supply temperature | The pulsed flow control method improves the efficiency of cooling/heating unit systems at different temperatures, providing more precise capacity control at partial load and requiring lower initial equipment cost. |
| [120] | 2018 | United States/ Office building | Simulation | AHU + RF | Distributed model predictive control, Feedback control | Predictive control reduced system power consumption by 27 % compared to feedback control |
| [121] | 2019 | China/ Laboratory | Experiment | AHU + RF | Model predictive control, Proportional-integral-derivative control (PID control) | Compared with PID controller, model predictive control controller has a shorter response time, better stability, and 17.5 % energy saving. |
| [122] | 2019 | United States/ Office building | Experiment | AHU + RF | Model predictive control, Feedback control | Model predictive control used peak-valley electricity to save about 34 % of the cost of system and 29–50 % less energy than an all-air system in the same building. |
| [16] | 2020 | China/Office building | Simulation | DOAS + RFC | Intermittent control, Night operation, Supply water temperature curves | The radiant surface reaches its maximum cooling effect approximately 1 h after it is turned off. Daytime cooling energy consumption is low, while nighttime cooling reduces the peak cooling requirement of the chiller by 25 %. |
| [123] | 2020 | Belgium/Office building | Experiment | VS + RFC | Rule-based control, Model predict control | The cloud-based white-box model predictive control is implemented and can be operated remotely in an office building. Model predict control minimizes thermal comfort deviations and saves energy. |
| [124] | 2021 | China/Office building | Simulation | VS + RF | Variable flow and Variable air volume closed-loop control | The control strategy can respectively control the two cooling ends of the air supply and RF to reach the required temperature. |
| [125] | 2021 | Sweden/Office building | Experiment, Simulation | RF | Intermittent on/off control, Feedback control | The operational strategies applied to building in this study moderately affected the heat extraction rate of the buried pipe direct supply system. |
| [126] | 2022 | China/Office Building | Simulation | VS + RFC | Intermittent operation of standby cooling | Intermittent ventilation system scheme has good energy-saving effect. It allows for control of indoor dry bulb |

(continued on next page)

**Table 2** (*continued*)

| Reference | Year | Location/ Building type | Method | System | Control strategies | Main findings |
|---|---|---|---|---|---|---|
| | | | | | | temperature and dew point temperature during system idle periods, ensuring stable operation. |
| [60] | 2022 | Italy/Laboratory | Experiment, Simulation | FCS + RF | Intermittent control based on weather forecast | The strategy of adjusting the temperature setpoint based on the weather forecast data can alleviate building undercooling or overheating and recommend a forecast range of 6 h for the cooling season. |
| [11] | 2022 | China/Office building | Experiment | VS + RF | Intermittent control, Pre-cooling control | According to indoor initial thermal environment and thermal gain, the control method of RFCS is proposed to realize the dynamic optimal control. |
| [84] | 2022 | China/ Laboratory | Experiment | FCS + RF | Water supply temperature control, Intermittent control | Intermittent control reduces system energy consumption by increasing the cooling time of the RF and reducing the cooling time of the FC. |
| [27] | 2022 | China/Office building | Simulation | VS + RF | Collaborative control, ON/OFF control | The collaborative control strategy based on the PMV-based prediction overcame the hysteresis of the cooling energy supply and demand, and reduce fluctuation of energy consumption. |
| [127] | 2023 | China/Office building | Simulation | VS + RF | ON/OFF control, Water supply temperature control, Pre-cooling control | The application potential of control strategy is affected by climate. Optimizing control strategy can reduce the influence of outdoor climate on indoor thermal comfort. |

Note: TABS: thermo-active building system, VS: ventilation system, RF: radiant floor system, RFC: radiant floor/ceiling system, AHU: air handling unit, DOAS: dedicated outdoor air system, FC: fan coil.

gain scheduling, state-space multivariable, transfer function controllers, and nonlinear controllers. It operates on a series of predefined rules, building models through “if-then-else” statements [130].

Gain scheduling uses a set of linear controllers to regulate nonlinear system [131,132]. The scheduling variable of the gain scheduling can be the outdoor temperature, while the controlled variable can be the radiant layer temperature [32]. The technique can leverage previous operating data to optimize control variables and parameters and handle imprecise and uncertain inputs to produce signal responses. Therefore, it can provide a better solution for different radiant floor systems with different thermal masses [133].

State-space variable and transfer function approaches can be used to model radiant floor systems mathematically [18,134]. These methods enable the calculation of cooling loads or describe the energy interaction between the radiant floor and the room. Radiative and convective heat transfer coefficients can be determined through empirical values or experimentation. The delay time between the heat input of the radiant floor system and the regional air temperature can be determined based on the transfer function between the cold floor and the regional air temperature. This allows for a reduction in peak power and energy consumption of the system [135]. Rule-based control serves as the foundation for complex control, and it requires assumptions and simplifications based on the experience of designers when setting up the algorithm model. However, these assumptions and simplifications may limit the adaptability of the model.

### 3.2.3. Hybrid, soft-computing control

Hybrid, soft-computing control methods, such as artificial intelligence, fuzzy logic, genetic algorithm, nonlinear hybrid, and data-driven control, do not require complex learning procedures and can optimize control parameters by incorporating relevant empirical knowledge. Su et al. [136] used a genetic algorithm reverse neural network to optimize the anti-condensation control of the RFCS. The weights and thresholds of the reverse neural network were optimized using genetic algorithm to accurately forecast the pre-dehumidification time and energy consumption of the office. This allowed the designer to select the best control strategies. However, the results obtained through soft computing methods cannot determine whether they are the optimal solution [137,138].

Various methods are constantly reorganized and improved, making “soft computing” more and more refined [139]. Hybrid and soft computing methods have also been applied to analyze the dynamic performance of radiant floor systems, aiming to improve the efficiency of mining control data. Qin et al. [140] proposed a data-driven fuzzy logic model. The model utilized outdoor air temperature, outdoor relative humidity, and the average temperature of supply and return water as input, and floor surface temperature, indoor air temperature, and indoor air humidity as output. The method fuzzed the coupling variables of indoor air temperature and floor surface temperature. It was discovered that the hysteresis between floor surface temperature and indoor air temperature was insignificant.

Hybrid, soft-computing control is inherently nonlinear and does not rely on precise computational models or extensive calculations. Compared to traditional methods, it offers advantages in addressing issues of uncertainty, imprecision, and optimization.

### 3.2.4. Advanced control

The use of RFCS to control indoor environments is complicated due to various indoor and outdoor factors. The thermal inertia of building can affect the operating performance of the system. Advanced control strategies can address the complexity and limitations involved in balancing building energy consumption and indoor thermal comfort. By implementing advanced control in near-zero energy buildings with RFCS, higher energy efficiency and improved comfort can be achieved compared to original control strategy of the building [141].

Advanced control mainly includes model predictive control and adaptive control and requires comprehensive data and models challenging data and models. Its optimization targets are usually indoor thermal comfort and energy when applied to RFCS controls. Previous studies have investigated the application of advanced control in air conditioning systems [26,133,142]. The model predictive control can optimize the operating state of system in a future period by predicting disturbance. Weather forecasting and internal load forecasting provide effective basis for the execution of the method [15,143]. Adaptive control can perform TABS control for specific regions based on multiple linear regression and continue to learn and improve, allowing it to address indoor disturbances in a timely fashion [13]. The stability of advanced control can be threatened by several factors, and improvements in systems and models can mitigate these issues [109]. Despite the rapid development of hardware technology, model predictive control for RFCSs requires longer computational time for prediction. The complex design and high cost brought using advanced control in actual buildings still need to be considered.

### 3.3. Anti-condensation control

The building cooling load consists of both latent heat load and sensible heat load. Radiant floor system can only handle the sensible load, and cannot bear the indoor latent heat load. Excess humidity will cause discomfort for occupants, condensation on the radiant surface, and reduction of performance of radiant floor heat transfer. The cause of condensation on the radiant floor is when the surface temperature drops below the indoor dew point temperature. To address this issue and improve the cooling capacity of the system, it is important to lower the temperature of the radiant surface while lowering the indoor dew point [41,144]. The high thermal mass RFCS has been evaluated in hot and humid climates and found to be effective in multi-zone residential buildings [145].

The minimum recommended radiant floor temperature in the standard is 19 °C [14]. However, in actual buildings, the furniture will cause uneven temperature on the floor surface and make it difficult to accurately control the temperature of the floor surface. To prevent condensation, an anti-condensation method is used by maintaining the supply water temperature 1–2 °C higher than the indoor dew point temperature or turning off the system when the floor temperature drops below the indoor dew point temperature [146,147]. Based on the experimental study, the type of the radiation panel structure can influence the condensation limit, resulting in the condensation temperature difference between the dew point temperature and floor temperature reached 3.2∼6.5 °C. The waste of anti-condensation energy consumption can be reduced when anti-condensation applied in system based on the sub-cooling degree [148]. Compared with flow rate control, water temperature control is more effective in responding to radiant floor surface anti-condensation [149]. In addition to regulating radiant floor heating, the ventilation system also plays a crucial role [23,25]. It can be controlled by variable air volume according to different zones, schedules, or indoor humidity. Lim et al. [147] found that the combination of outdoor temperature feedback control and dehumidification control can reduce the operating time of the dehumidification system by half.

During the startup phase of the radiant floor system, there is also a high risk of condensation on the radiant surface. Pre-dehumidification control is used to solve the condensation problem during opening [136,150]. Pre-dehumidification refers to opening the ventilation system for a period before the start of the radiant floor system to ensure that the indoor environment meets the necessary standards. The control of pre-dehumidification time can avoid wasting unnecessary initial energy consumption, which can be calculated or predicted based on the thermal inertia parameters of the radiant floor [150].

The pre-dehumidification time is a critical factor in preventing condensation from forming on the radiant floor surface. Regrettably, only limited studies have analyzed this important aspect.

### 3.4. Evaluation indices for the control strategies

The comparison between different strategies can be divided into short-term and long-term evaluations. The short-term evaluation focuses on hourly comparisons of thermal comfort and energy consumption of different control strategies in a typical period. This evaluation will visually display indoor and system parameters using graphical representations [121]. It offers a detailed analysis of strategy operation, including parameter trends and system conditions. On the other hand, the long-term evaluation aims to assess the overall stability and performance of strategies throughout their entire cycle. It calculates the distribution hours of different parameter ranges, the average value of parameters, and the sum of parameters in the cycle [14,105,127]. Thermal comfort analysis mostly focuses on calculating the hours of the parameter distribution, expressed through the proportion of the distribution time, since mean values cannot represent extreme value parameters. The evaluation parameters of different strategies fall into three categories: thermal comfort parameters, economic parameters, and performance parameters.

#### 3.4.1. Thermal comfort

Indoor thermal comfort is a critical criterion for assessing the efficacy of control strategies. It encompasses both general thermal comfort and local thermal discomfort, with thermal comfort range of each evaluation index can be divided into three categories (as displayed in Table 3) [14].

*3.4.1.1. General thermal comfort.* The key factors affecting overall thermal comfort can be boiled down to six main ones: metabolic rate, thermal resistance of clothing, air temperature, radiant temperature, air velocity, and indoor air humidity [151]. Although satisfaction of occupants with the indoor environment can also be used to evaluate thermal comfort, objective evaluative criteria are typically employed when assessing system control strategies. While metabolic rate and thermal resistance of clothing are generally set as fixed values in research due to their relationship with personnel behavior, the evaluation of indoor thermal comfort is primarily based on the last four factors.

Indoor air temperature is often representative of the ambient air temperature of the occupant [151]. Typically, in experimental studies, temperature measuring points are placed at 1.1 m [95]. The recommended indoor air temperature by the International Organization for Standardization (ISO 7730) is between 24 and 26 °C [14]. Compared to traditional convection air conditioning systems, RFCSs can maintain better thermal comfort in buildings [117], with indoor air temperatures comfortably ranging between 25.8 and 29.2 °C [152]. The radiant floor system exchanges heat with the indoor heat source through both convective and radiant heat transfers and lower mean radiation temperature can increase the tolerance of indoor air temperature. It is essential to consider the indoor mean radiant temperature. However, evaluating thermal comfort can be achieved more comprehensively using operative temperature since it represents the impact of both air temperature and mean radiant temperature within the indoor environment. The equation for calculating indoor operative temperature is shown in Equation (1) [151], and Table 3 displays the recommended operative temperature ranges based on clothing insulation and metabolic rate of occupants.

$$t_o = At_a + (1\text{-}A)\overline{t_r} \tag{1}$$

where $t_o$ is the operative temperature; $t_a$ is the average air temperature; $\overline{t_r}$ is the mean radiant temperature; $A$ is a coefficient as a function of the average air speed (When the average air speed <0.2 m/s, $A$ is 0.5; when the average air speed is in the range of 0.2–0.6 m/s, $A$ is 0.6; when the average air quality is in the range of 0.6–1 m/s, $A$ is 0.7.)

Radiant floor systems can follow the design values of conventional all-air systems for relative humidity and wind speed [153]. Under the standard indoor temperature of 26 °C in summer, the indoor relative humidity range needs to be controlled at 40–60 % [14]. The thermal discomfort caused by higher indoor relative humidity can be compensated by lower mean radiant temperature [152], or integrated with dehumidification equipment to overcome. The indoor relative humidity design values for rooms that use dehumidification are shown in Table 3 [154]. Since the system often works in conjunction with ventilation systems, Indoor air velocity need to be considered. To increase energy efficiency and reduce consumption, ventilation volume is based on indoor carbon dioxide concentration and minimum air change ratio in the room [71,155]. This ensures indoor fresh air demand and keeps the indoor air velocity below the limit of 0.24 m/s. Although some tropical countries have local standards for minimum indoor wind speed [35], it is rarely used as an evaluation index for control strategies.

Thermal comfort is an essential factor in evaluating indoor environments, and predicted mean vote/predicted percentage dissatisfied (PMV/PPD) is the most commonly used framework [27], mainly used to evaluate instantaneous thermal comfort indoors. For indoor parameters involving a certain time period or operating cycle, it is necessary to

**Table 3**
Range of different thermal comfort parameters [14,154].

| Category | Operative temperature (°C) | Design relative humidity for dehumidification (%) | Maximum mean air velocity (m/s) | PMV | PPD (%) | $PD_1$ (%) | $PD_2$ (%) | Minimum floor surface temperature (°C) |
|---|---|---|---|---|---|---|---|---|
| A | 23.5–25.5 | 50 | 0.12 | −0.2–0.2 | <10 | <3 | <10 | 19 |
| B | 23–26 | 60 | 0.19 | −0.5–0.5 | <20 | <5 | <10 | 19 |
| C | 22–27 | 70 | 0.24 | −0.7–0.7 | <30 | <10 | <15 | 17 |

Note: [a] The criteria for Vertical air temperature difference is 1.1 and 0.1 m above floor.
[b] The criteria for operative temperature and maximum mean air velocity are based on typical levels of activity, for clothing of 0.5 clo in summer.

quantify the number of hours beyond the comfort zone based on measurement or simulation results. The equations for calculating the number of hours beyond the PMV comfort zone and the adaptive model comfort zone is as follows [151]:

$$EH_p = \sum H_{disc} \tag{2}$$

where $EH_p$ is the exceedance hours calculated for the PMV comfort zone; $H_{disc}$ is a discomfort hour ($H_{disc} = 1$ if $|PMV|$ - 0.5 > 0 and 0 otherwise).

$$EH_t = \sum \left(H_{>upper} + H_{<lower}\right) \tag{3}$$

where $EH_t$ is the exceedance hours calculated for the adaptive model comfort zone; $H_{>upper}$ and $H_{>lower}$ is are discomfort hours outside the comfort zone boundaries $\left[t_{lower}, t_{upper}\right]$, ($H_{>upper} = 1$ if $t_{op} > t_{upper}$ and 0 otherwise; $H_{>lower} = 1$ if $t_{op} < t_{lower}$ and 0 otherwise).

However, recent research found that PMV tends to overestimate the thermal sensation of occupants [156], especially when evaluating different system configurations [96]. This is mainly affected by uneven thermal conditions, and the difficulty in quantifying the view factor between the human body and the surrounding environment results in simplified calculations for mean radiant temperature [157], which in turn affects the values of operative temperature and PMV.

*3.4.1.2. Local thermal discomfort.* The evaluation of local discomfort includes vertical air temperature difference, warm/cold floor, and radiant temperature asymmetry [14]. The RFCS can create a vertical air temperature difference [94]. The vertical temperature gradient is influenced by the form of ventilation. It should be within 3 K from the ankle level to the head level [158]. The range of air temperature difference from the ankle level to the head level should also be limited. If the vertical air temperature difference is below 8 °C, Equation (4) can be used to determine the local discomfort ($PD_1$) caused by it [14].

$$PD_1 = \frac{100}{1 - \exp\left(5.76 - 0.856\Delta t_{a,v}\right)} \tag{4}$$

where $PD_1$ is the local discomfort caused by vertical air temperature difference; $\Delta t_{a,v}$ is the vertical are temperature difference.

The radiant floor system focus on the lower body and can achieve similar levels of thermal comfort at a higher surface temperatures [159]. Nevertheless, the human hands and feet are more sensitive to thermal comfort, and cold floors can easily cause local discomfort and coldness [160]. The investigation is required to comprehensively understand the subjective thermal sensation experienced by individuals on cold floor. The recommended minimum floor temperature is 19 °C in areas where sedentary or standing individuals wearing standard footwear are present [158]. The standardized threshold for localized thermal comfort can vary significantly depending on temporal conditions and requires appropriate adjustments based on the floor surface material and occupant behavior [95]. Equation (5) demonstrates the effect of a cold floor ($PD_2$) on local thermal discomfort [14] (Equation (5) does not consider the long-term operation of electrically heated floors or situations involving barefoot contact by occupants).

$$PD_2 = 100–94\cdot\exp\left(-1.387 + 0.118t_f - 0.0025t_f^2\right) \tag{5}$$

where $PD_2$ is the local discomfort caused by cold floor; $t_f$ is the temperature of the floor surface.

There are temperature variations in the radiation between different surfaces within indoor environments, thus an evaluation of the indoor temperature asymmetry is needed within the system. The room with RFCS can easily result in vertical temperature differences in the radiation. It can lead to discomfort when exposed to for extended periods [161]. Among the three local thermal discomfort indicators, the impact of radiation temperature asymmetry on discomfort is least described in relation to cold floors. Radiation temperature asymmetry can be used to quantify the effects of indoor uneven radiation. ASHRAE 55–2017 [151] set the maximum allowable temperature difference of 5 °C. The non-symmetric radiation effect cannot be balanced out between different parts of the human body, while outdoor conditions and the building envelope can impact the exchange of thermal radiation with the human body [159]. Occupiers located near windows may be subjected to non-symmetric radiation from multiple directions. Currently, there is limited research that considers indoor radiation asymmetry as an indicator when evaluating system control strategies.

### 3.4.2. Economy

Economic evaluation is a crucial factor in determining the feasibility of control strategies. Evaluation of economy considers both the initial investment cost and the operating cost of the system. However, it can be challenging to quantify these costs accurately due to variations in regional conditions. There are no specific normative constraints on evaluation scope, and the current evaluation criteria are based on the principle of “less is better.” As a result, costs are often minimized when incorporated as an expected goal in control strategies [13].

The evaluation of system operating costs for different control strategies mainly involves comparing system energy consumption or electricity costs. Energy consumption can be broken down into partial energy consumption and overall energy consumption, with refrigeration equipment and transportation energy making up the overall energy consumed. Comparisons for the entire cooling season are usually made for RFCS, and experimental testing may reduce the comparison time. Some regulations [155] stipulate an upper limit for the average energy consumption index of newly built buildings. On the other hand, the difference of electricity costs is mainly affected by the operating time of the system, the thermal inertia of the system, and the peak valley electricity price [162]. While initial investment is minimally affected by the control strategy, different methods do require different configurations of system components and control accuracy, leading to cost differences [81,122]. The economic gap between two compared radiant floor cooling systems can be measured by the payback period, which refers to the number of years needed for reduced operating costs to repay the high initial investment cost of the system. The evaluation of payback period is of great significance for high-cost and low-energy consumption RFCSs, such as systems utilizing renewable energy or new radiant floor structures.

### 3.4.3. Performance of systems

To optimize system performance and efficiency, it is important to consider internal and external adjustments. Exergy is the part of energy that can be maximally converted into work when the system undergoes a reversible transformation from any state to equilibrium with the reference state. It emphasizes the efficient utilization of energy and is an important concept in energy analysis. Like economic evaluation, there is no specific scope or limitation for exergy analysis. However, it is an effective tool used to assess operating performance and potential of a system for optimization under varying conditions [163]. Exergy analysis is based on combining the first law of thermodynamics with the second law of thermodynamics [164]. This analysis can determine the impact of operating temperatures and energy and flow rates within the system [165]. Moreover, exergy analysis can also be utilized as a method for system evaluation. To analyze the system, an equilibrium equation must be established in advance, as demonstrated in Equation (4) [69,163].

$$\text{Exergy input} + \text{Exergy consumed} = \text{Exergy stored} + \text{Exergy output} \quad (4)$$

Exergy analysis often overlooks the causes of exergy loss and the utilization of internal resources. The commonly used evaluation indicators include exergy loss and exergy efficiency. Exergy loss is a decrease in energy quality in a system, mainly occurring in cold source and transportation systems. Exergy analysis can evaluate exergy loss and efficiency. Exergy efficiency refers to the percentage of exergy used effectively in the input system. The closer the exergy efficiency approaches 1, the better the thermodynamic perfection of the system. The calculation equation for efficiency is shown in Equation (5) [69].

$$\eta_{ex} = 1 - \frac{\text{Exergy Loss}}{\text{Exergy input}} \quad (5)$$

The RFCS is efficient as a low-exergy system composed of multiple subsystems [69]. Dealing with small temperature differences, it is possible to minimize the exergetic value of the heat flux in relation to its energetic value [166,167]. However, conducting thermal analysis can be complex due to numerous design parameters. To improve accuracy and efficiency, optimizing the calculation process is necessary.

## 4. Application

### 4.1. Case studies

The use of radiant floor for heating is widespread, it is also effective for building heating during winter [149]. Nevertheless, there are relatively few architectural reports on radiant floor heating and cooling system. The cases where they have been implemented in practical buildings are summarized in Table 4. It is evident that buildings equipped with radiant floor heating and cooling systems exhibit high energy efficiency and provide significant economic benefits. This can be attributed to the use of natural cold sources like cooling towers or direct-ground cold source. Theoretically speaking, the natural cold source may be impacted by the environment, leading to unstable water supply temperatures, but performance results during testing have been consistently satisfactory. Excessive use of natural cold sources can be avoided by optimizing the utilization time of natural cold source [168]. The investigation of indoor thermal comfort is divided into measurement and questionnaire surveys. Although the radiation surface temperature is uneven due to pipeline laying and other factors [122], little research has explored the temperature distribution of radiant surface and asymmetric radiation. The occupants and test results generally meet the requirements for thermal comfort, barring special human interference. However, overcooling or overheating may still occur in certain periods [169,170]. In addition, the dehumidification control of the system can be affected by the behavior of residents [145]. In conclusion, the application results of the radiant floor heating and cooling system have achieved good application, especially in energy-saving buildings.

### 4.2. Climate types

Climate is an important factor in the application of RFCS, which can be classified into four types based on temperature and humidity: high temperature and high humidity, high temperature and low humidity, and low temperature and high humidity [84]. RFCS is subjects to climatic disturbances mainly from solar radiation, infiltration, and ventilation [176]. RFCS is used in conjunction with ambient energy to condition the building, the climate not only impacts the thermal comfort evaluation of the building's interior but also its energy efficiency [13,78, 177].

In low humidity areas, RFCS can operate independently in the indoor environment based on the control strategy used. But in high humidity areas, as mentioned in section 2.3, radiant floor system needs to be integrated with ventilation systems to overcome climate effects [46,127]. The use of RFCS has grown quickly in high-humidity areas, and it promotes energy efficiency in high humidity environments [11]. Li et al. [177] found that RFCS is suitable for all climate zones in the United States. In fact, RFCS is more energy efficient in environments with lower humidity than in environments with higher humidity due to the high energy consumption of cooling and dehumidification systems [23,84]. The pre-cooling strategy can be used to reduce the peak cooling load and increase the cooling capacity in high temperature climate. Chandrashekar and Kumar [67] performed pre-cooling on a RFCS in a university building and found that the pre-cooling effect shifted the peak indoor temperature by 2 h and reduced energy consumption. RFCS demonstrates impressive self-regulating capabilities in high solar radiation environments. The radiant floor has a cooling emission rate of 39–50 $W/m^2$ when facing a mixture of cooling loads (convection and radiant), while the radiant floor has a cooling emission rate of 150–226 $W/m^2$ when only receiving short wave radiation (solar energy) [178]. However, the intermittent operation of the system would be significantly influenced by the intensity of solar radiation [179]. The application of RFCS in transitional seasons is easy to cause simultaneous cooling and heating, which leads to energy waste [20].

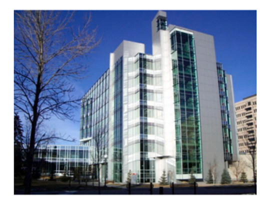
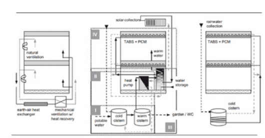
With the influence of human activities on the environment, the climate environment in the same area is also constantly changing. To promote the application of RFCS in various regions of the world, the recommendations for the effective implementation of RFCS in different climates are summarized (Fig. 11). Normally, the recommendations are affected by additional limitations, for example, natural night ventilation needs to consider rainy days and air pollution. Further research is needed on the optimal operating parameters of RFCS under different climate types to avoid both condensation on radiant surfaces and energy inefficacy [127]. Some traditional control strategies have been combined with climatic conditions, adjusting water supply parameters of RFCS according to the outdoor conditions [11,24,180]. Advanced control strategies [15,112] also use weather forecasting to predict and correct the next operation of the system, thus maintaining better thermal comfort in the room.

### 4.3. Building types

RFCS can be used in many types of buildings, such as office buildings [11,181], residential buildings [25,145], hospitals [177], educational buildings [19], museums [182], airports [30,183], etc. The physical characteristics of the building will affect the system type and control strategy selection of the RFCS and indoor thermal comfort [176].

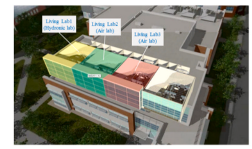
Most of the current research on RFCS is focused on commercial buildings [184]. These buildings have a small shape factor that makes them less susceptible to outdoor climate. Moreover, the working hours occupancy pattern of some commercial buildings is relatively uniform. Due to commercial buildings tendency to maintain positive pressure, the changes in indoor humidity load caused by infiltration can be ignored [13]. Although indoor positive pressure is beneficial for reducing the pollution of outdoor air, it can cause moisture to penetrate the building envelope. So, in high outdoor air quality or dry climates, balanced ventilation or slight negative pressure will be preferred indoors. Talami and Jakubiec [17] performed a sensitivity analysis of 13 design

**Table 4**
Application cases of radiant floor cooling and heating system.

| Reference | Year | Location | Climates | Building type | System | System cold/heat source | Monitoring period | Building diagram |
|---|---|---|---|---|---|---|---|---|
| [171] | 2005 | Hamburg, Germany | Temperate marine climate | Office building | VS + RF | CHP-plant, the condensing boiler, direct-ground cold source | July 2002–Aug. 2002 |  |
| [19] | 2007 | Biberach, Germany | Temperate marine climate | Vocational training school | VS + RF | Groundwater, heat pump, boiler | 2005 |  |
| [19] | 2007 | Aachen, Germany | Temperate marine climate | Office building | VS + RF | Borehole heat exchangers, heat pump | 2005 |  |
| [169] | 2009 | Calgary, Canada | Temperate continental climate | the ICT Building at the University of Calgary | VAV + RFC | Cooling coils, the campus water network | 2004, 2006 |  |
| [168] | 2010 | Germany | Temperate marine climate | House | VS + RFC | Rainwater storage tank, heat pump, solar collector | 2006–2007 |  |
| [83] | 2015 | Xian, China | Moist continental warm temperate monsoon climate | Airport | AHU + RF | Cooling tower, water chiller, heat exchange station | – |  |
| [172] | 2016 | Ancona, Italy | Subtropical humid climate | the Leaf House | AHU + RF | Geothermal heat pump, ground coupled heat exchanger solar collector, boiler | 2010 |  |
| [173] | 2016 | Denmark | Temperate marine climate | House | AHU + RF | Heat pump | Sep. 26, 2013–10 Oct. 2014 |  |
| [174] | 2017 | Colorado, United States | Temperate continental climate | Educational building | VS + RF | Cooling tower, natural gas condensing boiler system | 2016–2017 |  |

(*continued on next page*)

**Table 4** (*continued*)

| Reference | Year | Location | Climates | Building type | System | System cold/heat source | Monitoring period | Building diagram |
|---|---|---|---|---|---|---|---|---|
| [174] | 2017 | State of Oregon, United States | Temperate maritime climate | The Lovejoy Opsis Building | VS + RFC | Cooling tower, photovoltaic system | 2016–2017 |  |
| [122] | 2019 | Indiana, United States | Continental humid climate | Herrick Building | AHU + RF | Chiller, gas boiler | 27 Jan. 2018–5 Feb. 2018 and 13 Aug. 2017–22 Aug. 2017 |  |
| [175] | 2022 | Shandong, China | Warm temperate continental monsoon climate area | Office building | VS + RF | Direct-ground cold source, heat pump | June 2015–Aug. 2015 |  |

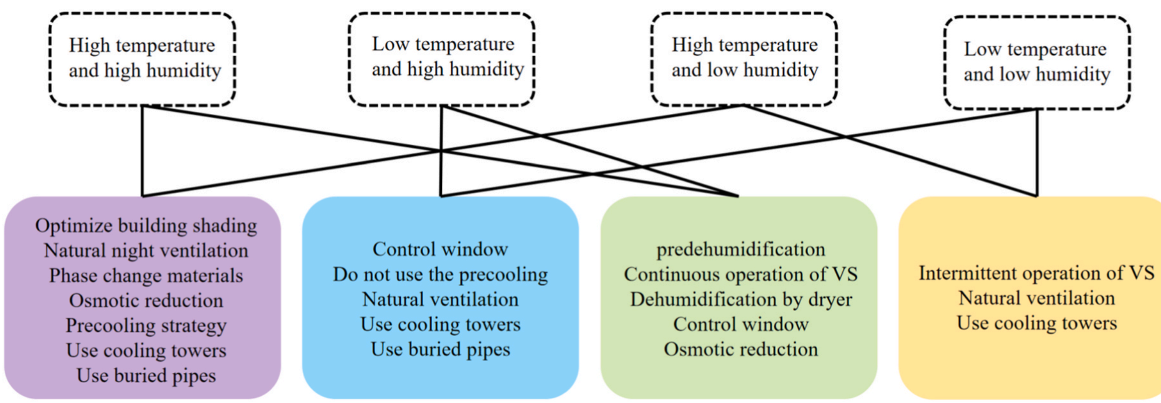



**Fig. 11.** Summary of suggestions for the application of RFCS in different climate types.

parameters for office buildings with RFCS installed, found that solar heat gain coefficient and area ratio of window to wall played a key role in thermal comfort, operation, and energy consumption of RFCS. It was determined that buildings with square or compact rectangular shapes achieved better energy performance. The control of a system is typically based on the difference in heat loss or gain and the heat or cooling required for the typical room [41]. The commercial building area is relatively large, and the buildings will be divided into areas based on the north-south direction to ensure the accuracy of system control [41]. In different commercial building types, the average energy saving of RFCS varies between 6.84 % and 48.0 % [177].

The behavior of occupants in residential buildings is a crucial factor in the application of RFCS. Random occupant behavior significantly affects the cooling demand and thermal comfort of the RFCS, and a good control strategy needs to adapt to various occupant behaviors [126, 185]. The research on the control of RFCS in residential buildings focuses more on conventional control strategies (as shown in Table 2). Unlike in office buildings, the control strategies of RFCS in residential buildings are more reliant on external climate conditions and conventional strategies [41]. Furthermore, the use of lighter-weight radiant floor in residential buildings can also reduce the response time of the system and provide better thermal comfort for the interior. Andersen et al. [71] studied the operation of the RFCS in residential buildings and discovered that the RFCS generates higher peak temperatures than the all-air cooling system. Due to the high insulation standards of buildings and the low energy efficiency of the system during nighttime, apartments or single-family residences are usually controlled as one control area [41].

The building envelope structure connects the indoor climate environment with the external environment, and its insulation performance can have a significant impact on building energy consumption [186]. For building envelope structures using RFCS, their thermal storage capacity, permeability, and internal surface heat transfer need to be considered [23,82]. The thermal resistance of the envelope can significantly impact system operation [187]. Radiant floor systems cool the building envelope, which can lead to long response times and wasted energy when the envelope has considerable heat storage capacity. In fact, RFCS has shown positive results when applied in high-rise buildings [19]. Large surface areas of transparent materials are utilized in buildings, causing excessive internal surface heat and transmission of solar radiation [107]. Large space buildings can vertically divide space, effectively cooling only the occupied space. The radiant floor will be maximized cooling capacity under solar radiation, which will also increase the temperature difference between the supply and return water [83]. It is recommended to combine natural ventilation, natural cold source, and sunshade design for optimization. If the high-quality interconnection and linkage between the internal functions of buildings and the radiant floor cooling systems are achieved, it is expected to bring more opportunities for the radiant floor cooling systems.

## 5. Discussion

### 5.1. Floor structure and ventilation

Although several conventional floor structures have been proposed in standards, there is still a lack of detailed research and data references on the characteristics of new composite materials. Radiant floors treat the sensible heat load indoors through both radiant and convective heat transfer, and the thermal performance of multi-layer floors would be significantly impacted by the pipe spacing and surface material. The piping materials (PE-X, PE-RT, PB, and PP, etc.) and surface materials of radiant floor heating systems of radiant floor systems, should possess excellent thermal conductivity. In contrast, insulation materials need to have good insulating properties to reduce downward heat loss. Research on the composition materials of radiant floor systems, particularly in studying the thermal conductivity under various operating conditions, is primarily conducted through experimental methods. It should be noted that the surface temperature of the floor is non-uniform, and it is influenced by solar radiation and furniture arrangement. This is not only hindering anti-condensation but also hampering cooling. The inclusion of a high thermal conductivity matrix in the floor can effectively improve the issue [52]. Accurately estimating the thermal performance of radiant floor systems is beneficial for optimizing floor structures. However, there is limited research on how integrating different types of radiant floor systems into a system affects long-term energy efficiency of the system. In particular, when considering cost variations in innovative designs of radiant floor structures, payback period becomes a crucial criterion in engineering design. It is important to evaluate the extent to which energy savings offset the high costs of radiant floor. Many studies focus on enhancing the responsiveness or cooling capacity of floor [29,52]. For instance, the radiant panel with a short response time may eliminate the need for pre-cooling strategies. Improvement of the construction reliability and anti-condensation performance of radiant floors would hold potential for the application of RFCS.

The ventilation system is the sole bearer of indoor latent load and generally employs cooling dehumidification. Dehumidifiers may also be utilized in situations with high latent load. The capacity of the ventilation system is closely related to the capacity of the radiant system [188]. Numerous studies have documented that the energy efficiency of ventilation systems is lower than that of radiant systems, which motivates minimizing the energy consumption of ventilation. Approximately 24 % of studies set the ventilation air change rate at 0.5–1 $h^{-1}$, 47 % at 1-2 $h^{-1}$. The remaining 29 % opt to design the air change rate based on the occupants indoors. However, the improper use of the ventilation system may weaken the impact of the radiant floor system on the indoor environment, especially when convective heat gains are dominant [178]. Therefore, it is recommended to improve the floor materials and structure to lower the supply water temperature of the radiant system and increase the capacity of the radiant floor system.

### 5.2. System operation control

The design of control strategies for RFCS aims to achieve real-time responsiveness to the building interior conditions while reducing energy consumption. Extensive research has been conducted on control strategies, employing simulation and experimentation as the primary research methods. Simulation methods often utilize predefined internal loads and occupant behavior, leading to building load variations that heavily depend on external climate conditions. While abrupt thermal environments provide greater resemblance to actual conditions, there is insufficient research on control strategies in such environments. Occupant behavior and equipment accuracy also affect the implementation of control strategies, resulting in deviations between simulation and experimental results [75]. The importance of precooling strategies in system control increases as the heat storage capacity of RFCS and the internal loads of buildings increase. Model predictive control shows an 11 %–15 % difference in electricity between RFCS with and without precooling strategies [13]. Decoupling control of indoor parameters is an interesting approach to mitigate condensation risks while improving operational performance of radiant floor cooling systems. Through literature studies, the adoption of advanced control strategies to replace conventional ones in actual buildings is limited, presenting challenges to their widespread application. The model established in advanced strategies is prone to deviate from the actual building, resulting in control imbalance. Although the model will be validated based on actual building measurement data, changes in equipment and building conditions can compromise the performance of the model. Many studies highlight the need for future optimization of system models. Multi-stage calibration of floor cooling systems can improve model accuracy by 50 % [189]. Consequently, the development of equipment fault early monitoring and predictive diagnosis [190,191] based on RFCS is vital to ensure stable system operation and effective implementation of control strategies.

The initial investment of RFCS can be higher than that of traditional air conditioning systems, and an economic assessment is required to determine its feasibility for application. Exergy analysis provides a more accurate evaluation of the system overall performance. Exergy losses typically occur in transportation and cold source systems, and exergy analysis of RFCS helps explore the system potential for minimizing losses. However, there are relatively few studies on optimizing RFCS operation control based on exergy analysis. Relative comparison can be employed as a method for evaluating control strategies, involving the comparison of multiple cases to a base case or pairwise comparisons [112,123]. Many control strategies have been proven strong application potential, but the choice of a base strategy they contrast varies across studies. Therefore, reliable evaluation methods are needed to guide the selection and application of strategies in practical projects.

### 5.3. Risk of condensation

The primary limitation of RFCS is the occurrence of condensation on the floor surface. Therefore, the surface temperature of the radiant floor is typically maintained above the dew point temperature. When the radiant floor system operates under high loads, measures need to be taken to reduce the dew point temperature to prevent condensation. The improvement of airtightness and insulation performance of the building envelope and incorporation of shading can mitigate outdoor environmental influences [79]. Additionally, an integrated auxiliary system can assist in managing the latent and sensible heat loads inside the space. Different indoor environment of the same building zone needs to be regulated through air systems. In cases of significant latent load, using separate dehumidification and cooling systems is preferable [87]. Pre-dehumidification is necessary before activating the radiant floor, and due to the thermal inertia of the system, it is still crucial to continue controlling indoor humidity after the radiant system is turned off. Airflow design near the floor and indoor heat source design can also indirectly reduce the condensation risk of floor, but there is significant uncertainty in system operation.

The measures for releasing condensation on radiant floor mainly focus on system regulation, and the design of floor materials is also an important aspect, such as applying a film layer to the radiant surface to isolate the air and prevent condensation (Fig. 12 [192]). This film layer ensures the transmission of infrared radiation between the radiant surface and the indoor environment. Consequently, the surface temperature of the film is maintained above the dew point temperature, ensuring satisfactory indoor thermal comfort even when the supply water temperature of the radiant system is low. Passive condensation prevention is highly appealing for the application of RFCS [192,193]. However, the mechanical performance of materials applied on the surface of radiant floor poses a significant technical challenge. If this challenge is

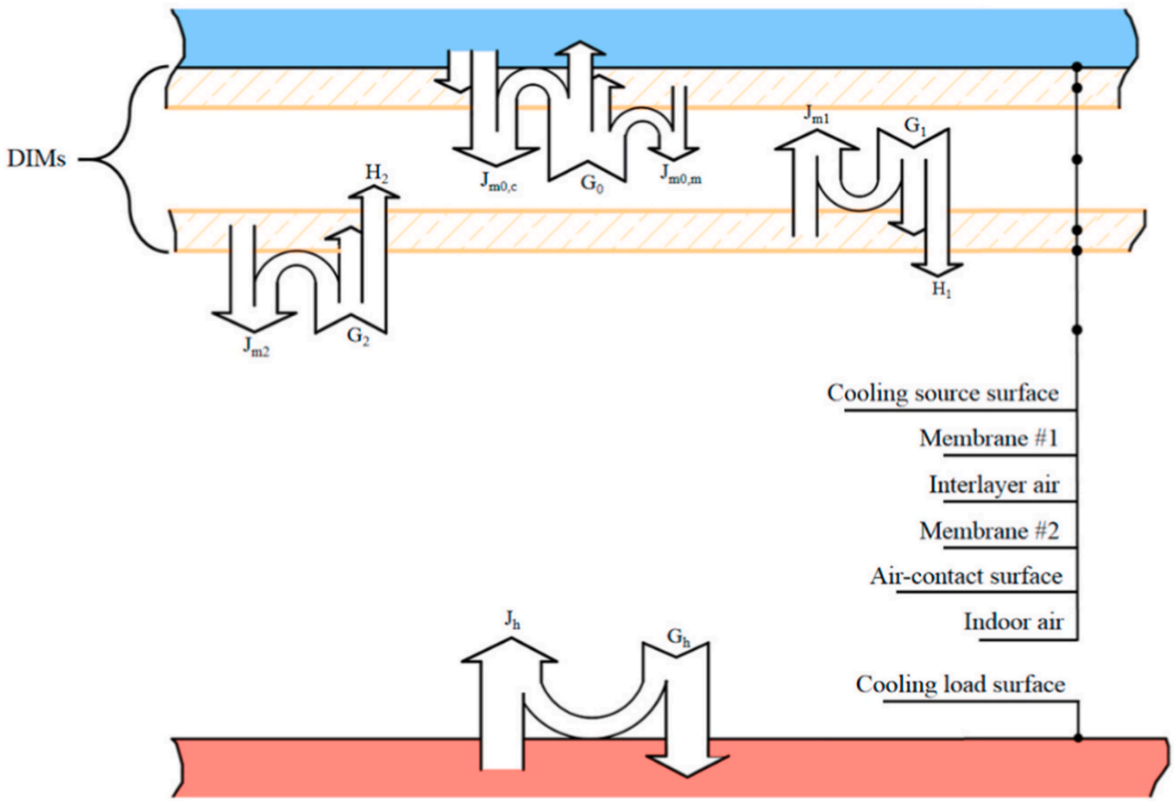



**Fig. 12.** Schematic representation of radiation heat transfer for a condensation-free radiant cooling system with double-skin infrared-transparent membranes [192].

overcome, it will greatly enhance the performance potential of radiant floor systems. Thus, it is recommended to conduct research from various perspectives, such as floor structure and system controls, in order to mitigate the risk of condensation on the radiant surface and simultaneously improve the cooling capacity of the system.

Risk assessment for condensation in RFCS is crucial for the possibility of system application. The condensation rate on the radiant surface of the floor is a basic index to evaluate the condensation on the floor surface [108], although it is seldom utilized in system evaluations. Building simulations provide a means for early assessment of both building dynamics and condensation risks [183,194]. As the maturity of the prediction algorithm, the risk of condensation can be accurately predicted based on models or equations without experiments and simulations [195]. However, despite the potential of this promising approach, its implementation in RFCS has not been reported in the literature.

### *5.4. Radiant floor heating and cooling system*

Radiant floor systems are commonly utilized for heating buildings; however, there are fewer applications that simultaneously integrate both radiant cooling and heating functions. For example, even in residential buildings equipped with radiant floor heating systems, split air conditioning units are still commonly selected for cooling. Compared to building heat load, the peak demand for building cooling load is large and load fluctuates is greater, and the efficiency of centralized cooling sources is low. Variable refrigerant flow system can achieve the same or better performance than RFCS under the same control strategy [13]. Therefore, it is necessary to explore the building and climate conditions that are suitable for the application of radiant floor cooling and heating systems, and develop efficient composite cooling sources. To achieve optimal cooling and heating effects with radiant floor system, it is essential to consider the heat transfer mechanism and design conditions [196].

With the increase or decrease in the number of buildings, building renovation and upgrading are gradually being valued [197]. In the process of construction and renovation, the integration of RFCS into buildings may provide opportunities for further expansion at a lower cost. Building retrofits present challenges beyond installation and maintenance, including complex strategy transitions and limitations of ventilation systems [46]. Clearly, incorporating thermal storage is encouraged in the design of RFCS, which requires exploration of the power grid and energy storage.

Radiant floor cooling and heating systems can be viable solutions for achieving nearly zero energy buildings [75]. It is worth noting that increasing the energy storage capacity and reducing the response time of the RFCS are both research hotspots, and the inherent relationship between the two has reference value for the application direction of the system. The coordination between climate and application scenarios should pay careful attention to fully meet energy and thermal comfort requirements.

## 6. Conclusion

In the context of rapid development in low-carbon energy, the RFCS has emerged as one of the most sustainable air conditioning systems. This review provided a comprehensive overview of the construction of radiant floors, the composition of radiant floor cooling systems, control strategies for systems, and anti-condensation. The review also conducted a thorough review of the application of RFCS to evaluate the balance between innovation and engineering design. Currently, research efforts are focused on the control and optimization, though there are still limitations in practice and innovation. Nonetheless, RFCSs still maintain a vibrant, and investigating the latest developments in various aspects can help in adapting to the energy transition. The main discussions can be summarized as follows:

The control of RFCS is one of the major challenges, which is closely tied to anti-condensation and system design. Consequently, research on RFCS primarily revolves around control strategies. Thermal comfort, economy, and performance are interconnected and serve as key indicators for selecting suitable control strategies. At present, non-predictive control strategies remain the dominant control strategies, although significant progress has been made in advanced control strategies. The selection of control strategies has implications for the climate adaptability and building scenarios suitability of the system. Thus, more attention should be paid to the combination of control and application. Condensation risk poses a limitation to RFCS, requiring active dehumidification for effective prevention. The most common RFCS involves integrating the radiant floor system with the ventilation system. However, care must be taken to ensure proper sizing of both systems to avoid compromising the cooling performance of the floor. There is a lack of research on passive condensation methods for investigating floor structures. In contrast, floor structure investigations have focused more on experimental testing. It is crucial to determine the characteristics of new materials and floor structures to provide valuable insights for engineering applications. On the other hand, the application and retrofitting of radiant floor cooling and heating systems are interesting research areas. On the path towards energy conservation and emission reduction, the radiant floor system would stand as a prominent contributor to the effective utilization of clean energy.

The following are proposed recommendations for future research, but not limited to:

➢ The design of radiant floors should prioritize condensation prevention, cost-effectiveness, and high performance to enhance the cooling capacity of such systems.
➢ Anti-condensation measures for RFCS should be better integrated with materials and control to enhance the system adaptability to different climates and building types.
➢ Control strategies for RFCS should consider robustness, durability, and system operation fault diagnosis. Advanced control strategies should replace conventional ones in existing buildings.
➢ The application of RFCS in buildings should explore options for retrofitting or integrating with radiant floor heating system to expand their scope of application.

## CRediT authorship contribution statement

**Mengying Cui:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Baisong Ning:** Writing – review & editing, Supervision, Methodology. **Xiaozhou Wu:** Writing – review & editing, Supervision, Methodology. **Moon Keun Kim:** Writing – review & editing, Supervision. **Bin Yang:** Writing – review & editing, Supervision. **Zhe Tian:** Writing – review & editing, Supervision. **Jiying Liu:** Writing – review & editing, Supervision, Methodology, Conceptualization, Project administration, Funding acquisition.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## Acknowledgements

This work was funded by the Natural Science Foundation of Shandong Province, China (ZR2021ME199, ZR2021ME237). This work was also supported by the Plan of Introduction and Cultivation for Young Innovative Talents in Colleges and Universities of Shandong Province (Lu Jiao Ke Han [2021] No. 51).

## References

[1] Iea, Technology and Innovation Pathways for Zero-Carbon-Ready Buildings by 2030, IEA, Paris, 2022. https://www.iea.org/reports/technology-and-innovation-pathways-for-zero-carbon-ready-buildings-by-2030.
[2] U. N. E. Programme, Global Status Report for Buildings and Construction: towards a Zero-Emission, Efficient and Resilient Buildings and Construction Sector, United Nations Environment Programme, Nairobi, 2022, 2022-11-9, https://wedocs.unep.org/20.500.11822/41133.
[3] C. Karmann, S. Schiavon, F. Bauman, Thermal comfort in buildings using radiant vs. all-air systems: a critical literature review, Build. Environ. 111 (2017) 123–131, https://doi.org/10.1016/j.buildenv.2016.10.020.
[4] S. Thapa, G.K. Panda, Energy conservation in buildings – a review, Int. J. Energy Eng. 5 (4) (2015) 95–112, https://doi.org/10.5963/IJEE0504001.
[5] M.M.S. Dezfouli, A.R. Dehghani-Sanij, K. Kadir, R. Suhairi, S. Rostami, K. Sopian, Is a fan coil unit (FCU) an efficient cooling system for net-zero energy buildings (NZEBs) in tropical regions? An experimental study on thermal comfort and energy performance of an FCU, Results in Engineering 20 (2023) 101524, https://doi.org/10.1016/j.rineng.2023.101524.
[6] M.D. Carli, B.W. Olesen, Field measurements of thermal comfort conditions in buildings with radiant surface cooling systems. Proceedings of the the 7th REHVA World Congress and Clima 2000 Naples 2001 Conference, Naples (Italy), 2001.
[7] R. Hu, J.L. Niu, A review of the application of radiant cooling & heating systems in Mainland China, Energy Build. 52 (2012) 11–19, https://doi.org/10.1016/j.enbuild.2012.05.030.
[8] R. Bean, B.W. Olesen, K.W. Kim, History of radiant heating & cooling systems: Part 2, ASHRAE J. 52 (2) (2010) 50–55.
[9] J. Le Dréau, P. Heiselberg, Sensitivity analysis of the thermal performance of radiant and convective terminals for cooling buildings, Energy Build. 82 (2014) 482–491, https://doi.org/10.1016/j.enbuild.2014.07.002.
[10] K.-N. Rhee, B.W. Olesen, K.W. Kim, Ten questions about radiant heating and cooling systems, Build. Environ. 112 (2017) 367–381, https://doi.org/10.1016/j.buildenv.2016.11.030.
[11] J. Ren, J. Liu, S. Zhou, M.K. Kim, S. Song, Experimental study on control strategies of radiant floor cooling system with direct-ground cooling source and displacement ventilation system: a case study in an office building, Energy 239 (2022) 16, https://doi.org/10.1016/j.energy.2021.122410.
[12] G.P. Henze, C. Felsmann, D.E. Kalz, S. Herkel, Primary energy and comfort performance of ventilation assisted thermo-active building systems in continental climates, Energy Build. 40 (2) (2008) 99–111, https://doi.org/10.1016/j.enbuild.2007.01.014.
[13] T. Zakula, P.R. Armstrong, L. Norford, Advanced cooling technology with thermally activated building surfaces and model predictive control, Energy Build. 86 (2015) 640–650, https://doi.org/10.1016/j.enbuild.2014.10.054.
[14] ISO, ISO 7730: 2005, Ergonomics of the Thermal Environment– Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria, International Standardization Organization, Geneva, 2005. ISO 7730.
[15] M. Schmelas, T. Feldmann, E. Bollin, Adaptive predictive control of thermo-active building systems (TABS) based on a multiple regression algorithm, Energy Build. 103 (2015) 14–28, https://doi.org/10.1016/j.enbuild.2015.06.012.
[16] X. Sui, H. Wang, M. Qu, H. Liu, Thermal response characteristics of intermittently cooled room with tube-embedded cooling slab and optimization of intermittent control, Energies 13 (7) (2020) 1568, https://doi.org/10.3390/en13071568.
[17] R. Talami, J.A. Jakubiec, Early-design sensitivity of radiant cooled office buildings in the tropics for building performance, Energy Build. 223 (2020) 110177, https://doi.org/10.1016/j.enbuild.2020.110177.
[18] B. Ning, S. Schiavon, F.S. Bauman, A novel classification scheme for design and control of radiant system based on thermal response time, Energy Build. 137 (2017) 38–45, https://doi.org/10.1016/j.enbuild.2016.12.013.
[19] J. Pfafferott, D. Kalz, Thermo-active Building Systems: High-Comfort, Energy-Efficient Heating and Cooling of Non-residential Buildings, 2007. Bonn (Germany).
[20] E. Fabrizio, S.P. Corgnati, F. Causone, M. Filippi, Numerical comparison between energy and comfort performances of radiant heating and cooling systems versus air systems, HVAC R Res. 18 (4) (2012) 692–708, https://doi.org/10.1080/10789669.2011.578700.
[21] A.K. De Wit, C.J. Wisse, Hydronic circuit topologies for thermally activated building systems – design questions and case study, Energy Build. 52 (2012) 56–67, https://doi.org/10.1016/j.enbuild.2012.05.010.
[22] K. Zhao, X.-H. Liu, Y. Jiang, Dynamic performance of water-based radiant floors during start-up and high-intensity solar radiation, Sol. Energy 101 (2014) 232–244, https://doi.org/10.1016/j.solener.2013.12.033.
[23] Z. Tian, J.A. Love, Application of radiant cooling in different climates: assessment of office buildings through simulation. Proceedings of the Eleventh International IBPSA Conference, Glasgow (Scotland), 2009, https://doi.org/10.1080/19401490902893757.
[24] D. Song, T. Kim, S. Song, S. Hwang, S.-B. Leigh, Performance evaluation of a radiant floor cooling system integrated with dehumidified ventilation, Appl. Therm. Eng. 28 (11) (2008) 1299–1311, https://doi.org/10.1016/j.applthermaleng.2007.10.020.
[25] A. Zarrella, M. De Carli, C. Peretti, Radiant floor cooling coupled with dehumidification systems in residential buildings: a simulation-based analysis, Energy Convers. Manag. 85 (2014) 254–263, https://doi.org/10.1016/j.enconman.2014.05.097.

[26] M.A. Hassan, O. Abdelaziz, Best practices and recent advances in hydronic radiant cooling systems – Part II: simulation, control, and integration, Energy Build. 224 (2020) 110263, https://doi.org/10.1016/j.enbuild.2020.110263.
[27] J. Ren, J. Liu, S. Zhou, M.K. Kim, J. Miao, Developing a collaborative control strategy of a combined radiant floor cooling and ventilation system: a PMV-based model, J. Build. Eng. 54 (2022) 20, https://doi.org/10.1016/j.jobe.2022.104648.
[28] L. Navarro, A. De Gracia, S. Colclough, M. Browne, S.J. Mccormack, P. Griffiths, L.F. Cabeza, Thermal energy storage in building integrated thermal systems: a review. Part 1. active storage systems, Renew. Energy 88 (2016) 526–547, https://doi.org/10.1016/j.renene.2015.11.040.
[29] M.A. Abdel-Mawla, M.A. Hassan, A. Khalil, Phase change materials in thermally activated building systems: a comprehensive review, Int. J. Energy Res. 46 (2022) 11676–11717, https://doi.org/10.1002/er.8035.
[30] K. Zhao, X.-H. Liu, Y. Jiang, Application of radiant floor cooling in large space buildings – a review, Renew. Sustain. Energy Rev. 55 (2016) 1083–1096, https://doi.org/10.1016/j.rser.2015.11.028.
[31] C. Zhang, M. Pomianowski, P.K. Heiselberg, T. Yu, A review of integrated radiant heating/cooling with ventilation systems- Thermal comfort and indoor air quality, Energy Build. 223 (2020) 19, https://doi.org/10.1016/j.enbuild.2020.110094.
[32] J. Romani, A. De Gracia, L.F. Cabeza, Simulation and control of thermally activated building systems (TABS), Energy Build. 127 (2016) 22–42, https://doi.org/10.1016/j.enbuild.2016.05.057.
[33] D. Olsthoorn, F. Haghighat, A. Moreau, G. Lacroix, Abilities and limitations of thermal mass activation for thermal comfort, peak shifting and shaving: a review, Build. Environ. 118 (2017) 113–127, https://doi.org/10.1016/j.buildenv.2017.03.029.
[34] A. Hesaraki, N. Huda, A comparative review on the application of radiant low-temperature heating and high-temperature cooling for energy, thermal comfort, indoor air quality, design and control, Sustain. Energy Technol. Assessments 49 (2022) 13, https://doi.org/10.1016/j.seta.2021.101661.
[35] E.M. Saber, K.W. Tham, H. Leibundgut, A review of high temperature cooling systems in tropical buildings, Build. Environ. 96 (2016) 237–249, https://doi.org/10.1016/j.buildenv.2015.11.029.
[36] J. Lizana, R. Chacartegui, A. Barrios-Padura, C. Ortiz, Advanced low-carbon energy measures based on thermal energy storage in buildings: a review, Renew. Sustain. Energy Rev. 82 (2018) 3705–3749, https://doi.org/10.1016/j.rser.2017.10.093.
[37] F. Zhang, H.A. Guo, Z.X. Liu, G.Q. Zhang, A critical review of the research about radiant cooling systems in China, Energy Build. 235 (2021) 16, https://doi.org/10.1016/j.enbuild.2021.110756.
[38] J. Shinoda, O.B. Kazanci, S.-I. Tanabe, B.W. Olesen, A review of the surface heat transfer coefficients of radiant heating and cooling systems, Build. Environ. 159 (2019) 106156, https://doi.org/10.1016/j.buildenv.2019.05.034.
[39] Iso, Building Environment Design — Embedded Radiant Heating and Cooling Systems –Part 5: Installation: Switzerland, International Standardization Organization, 2021.
[40] J. Babiak, B.W. Olesen, D. Petráš, Low Temperature Heating and High Temperature Cooling: REHVA GUIDEBOOK No 7, 2007.
[41] Iso, Building Environment Design — Embedded Radiant Heating and Cooling Systems –Part 6: Control: Switzerland, International Standardization Organization, 2021.
[42] H. Tang, T. Zhang, X. Liu, Y. Jiang, Study on the pulsed flow control on radiant cooling and heating systems in part load, Procedia Eng. 205 (2017) 11–18, https://doi.org/10.1016/j.proeng.2017.09.928.
[43] M. Moreira, J. Dias-De-Oliveira, C. Amaral, F. Neto, T. Silva, Outline of the incorporation of phase change materials in radiant systems, J. Energy Storage 57 (2023) 106307, https://doi.org/10.1016/j.est.2022.106307.
[44] Y. Fang, X. Zhang, C. Liu, Experimental study of lightweight radiant floor heating system with non-full-coverage heat-conducting plate, J. Southeast Univ. (Nat. Sci. Ed.) 52 (2022) 1104–1113, https://doi.org/10.3969/j.issn.1001-0505.2022.06.010.
[45] L. Qiu, Q. Li, Analyses on two paving types of floor heating. Proceedings of the 2011 International Conference on Computer Distributed Control and Intelligent Environmental Monitoring, 2011, https://doi.org/10.1109/CDCIEM.2011.527. Changsha (China).
[46] H.Q. Do, M.B. Luther, M. Amirkhani, Z. Wang, I. Martek, Radiant conditioning retrofitting for residential buildings, Energies 15 (2) (2022) 449, https://doi.org/10.3390/en15020449.
[47] S. Thomas, P.-Y. Franck, P. André, Model validation of a dynamic embedded water base surface heat emitting system for buildings, Build. Simulat. 4 (1) (2011) 41–48, https://doi.org/10.1007/s12273-011-0025-8.
[48] X. Xu, J. Yu, S. Wang, J. Wang, Research and application of active hollow core slabs in building systems for utilizing low energy sources, Appl. Energy 116 (2014) 424–435, https://doi.org/10.1016/j.apenergy.2013.09.064.
[49] H. Kitagawa, T. Asawa, T. Kubota, A.R. Trihamdani, K. Sakurada, H. Mori, Optimization of window design for ventilative cooling with radiant floor cooling systems in the hot and humid climate of Indonesia, Build. Environ. 188 (2021) 107483, https://doi.org/10.1016/j.buildenv.2020.107483.
[50] M.A. Abdel-Mawla, M.A. Hassan, A. Khalil, Impact of placement and design of phase change materials in thermally activated buildings, J. Energy Storage 56 (2022) 105886, https://doi.org/10.1016/j.est.2022.105886.
[51] T. Hai, H.A. Dhahad, J. Zhou, A. Abdelrahman, S.F. Almojil, A.I. Almohana, A. F. Alali, T.I. Kh, K. Sharma, M.A. Ali, K.T. Almoalimi, Implementation of artificial neural network in a building benefits from radiant floor heating/cooling enhanced by phase change materials, Eng. Anal. Bound. Elem. 146 (2023) 66–79, https://doi.org/10.1016/j.enganabound.2022.10.012.
[52] R. Ansuini, R. Larghetti, A. Giretti, M. Lemma, Radiant floors integrated with PCM for indoor temperature control, Energy Build. 43 (11) (2011) 3019–3026, https://doi.org/10.1016/j.enbuild.2011.07.018.
[53] L. Navarro, A. De Gracia, A. Castell, S. Álvarez, L.F. Cabeza, PCM incorporation in a concrete core slab as a thermal storage and supply system: proof of concept, Energy Build. 103 (2015) 70–82, https://doi.org/10.1016/j.enbuild.2015.06.028.
[54] S. Shukla, R. Daneshazarian, A. Mwesigye, W.H. Leong, S.B. Dworkin, A novel radiant floor system: detailed characterization and comparison with traditional radiant systems, Int. J. Green Energy 17 (2) (2020) 137–148, https://doi.org/10.1080/15435075.2019.1708366.
[55] J. Ma, Y. Yang, X. Zheng, B. Dai, D. Zhu, Q. Liu, Impact on heat storage performance of concrete radiant floor with finned water supply pipes, J. Build. Eng. 44 (2021) 103351, https://doi.org/10.1016/j.jobe.2021.103351.
[56] Y. Xu, B.B. Sun, L.J. Liu, X.Y. Liu, The numerical simulation of radiant floor cooling and heating system with double phase change energy storage and the thermal performance, J. Energy Storage 40 (2021) 102635, https://doi.org/10.1016/j.est.2021.102635.
[57] H. Kitagawa, T. Asawa, T. Kubota, A.R. Trihamdani, H. Mori, Thermal storage effect of radiant floor cooling system using phase change materials in the hot and humid climate of Indonesia, Build. Environ. 207 (2022) 108442, https://doi.org/10.1016/j.buildenv.2021.108442.
[58] H. Kitagawa, T. Asawa, T. Kubota, A.R. Trihamdani, Numerical simulation of radiant floor cooling systems using PCM for naturally ventilated buildings in a hot and humid climate, Build. Environ. 226 (2022) 109762, https://doi.org/10.1016/j.buildenv.2022.109762.
[59] W. Sun, Z. Zhang, Z. Wu, Y. Xu, Numerical modeling and optimization of annual thermal characteristics of an office room with PCM active–passive coupling system, Energy Build. 254 (2022) 111629, https://doi.org/10.1016/j.enbuild.2021.111629.
[60] S. Cesari, G. Emmi, M. Bottarelli, A weather forecast-based control for the improvement of PCM enhanced radiant floors, Appl. Therm. Eng. 206 (2022) 118119, https://doi.org/10.1016/j.applthermaleng.2022.118119.
[61] Z. Tian, J.A. Love, A field study of occupant thermal comfort and thermal environments with radiant slab cooling, Build. Environ. 43 (10) (2008) 1658–1670, https://doi.org/10.1016/j.buildenv.2007.10.012.
[62] P. Simmonds, S. Holst, S. Reuss, W. Gaw, Using radiant cooled floors to condition large spaces and maintain comfort conditions. Proceedings of the ASHRAE Winter Meeting, Texas (United States), 2000.
[63] B. Lehmann, V. Dorer, M. Gwerder, F. Renggli, J. Tödtli, Thermally activated building systems (TABS): energy efficiency as a function of control strategy, hydronic circuit topology and (cold) generation system, Appl. Energy 88 (1) (2011) 180–191, https://doi.org/10.1016/j.apenergy.2010.08.010.
[64] X. Gu, M. Cheng, X. Zhang, Z. Qi, J. Liu, Z. Li, Performance analysis of a hybrid non-centralized radiant floor cooling system in hot and humid regions, Case Stud. Therm. Eng. 28 (2021) 101645, https://doi.org/10.1016/j.csite.2021.101645.
[65] G. Salvalai, J. Pfafferott, M.M. Sesana, Assessing energy and thermal comfort of different low-energy cooling concepts for non-residential buildings, Energy Convers. Manag. 76 (2013) 332–341, https://doi.org/10.1016/j.enconman.2013.07.064.
[66] V. Echarri-Iribarren, N.H. Wong, A. Sánchez-Ostiz, Radiant floors versus radiant walls using ceramic thermal panels in mediterranean dwellings: annual energy demand and cost-effective analysis, Sustainability 13 (2) (2021) 588, https://doi.org/10.3390/su13020588.
[67] R. Chandrashekar, B. Kumar, Experimental investigation on energy saving potential for thermally activated buildings integrated with the active cooling system, ENERG SOURCE PART A 44 (3) (2022) 7585–7597, https://doi.org/10.1080/15567036.2022.2116132.
[68] M. Nasrabadi, D.P. Finn, Analysis of a low-temperature small approach open cooling tower integrated with radiant cooling and displacement ventilation for space conditioning in temperate climates, Adv. Build. Energy Res. 16 (6) (2022) 754–779, https://doi.org/10.1080/17512549.2022.2101524.
[69] O.B. Kazanci, M. Shukuya, B.W. Olesen, Theoretical analysis of the performance of different cooling strategies with the concept of cool exergy, Build. Environ. 100 (2016) 102–113, https://doi.org/10.1016/j.buildenv.2016.02.013.
[70] J.I. Villarino, A. Villarino, F.Á. Fernández, Experimental and modelling analysis of an office building HVAC system based in a ground-coupled heat pump and radiant floor, Appl. Energy 190 (2017) 1020–1028, https://doi.org/10.1016/j.apenergy.2016.12.152.
[71] M.E. Andersen, J. Schøtt, O.B. Kazanci, B.W. Olesen, Energy performance of water-based and air-based cooling systems in plus-energy housing. Proceedings of the 12th REHVA World Congress CLIMA 2016, Aalborg (Denmark), 2016.
[72] L.S.D. G, S.M.S. Nagendra, M.P. Maiya, Feasibility analysis of passive thermally activated building system for various climatic regions in India, Energy Build. 155 (2017) 352–363, https://doi.org/10.1016/j.enbuild.2017.08.083.
[73] D.E. Kalz, J. Pfafferott, S. Herkel, A. Wagner, Energy and efficiency analysis of environmental heat sources and sinks: in-use performance, Renew. Energy 36 (3) (2011) 916–929, https://doi.org/10.1016/j.renene.2010.09.003.
[74] M. Cui, Y. Song, Y. Mao, K. Yang, J. Liu, Z. Tian, Potential application of radiant floor cooling systems for residential buildings in different climate zones, Build. Simulat. 17 (4) (2024) 543–560, https://doi.org/10.1007/s12273-023-1098-x.
[75] P. Raftery, C. Duarte, S. Schiavon, F. Bauman, A new control strategy for high thermal mass radiant systems Permalink. Proceedings of the 2017 Building

Simulation Conference, San Francisco (United States), 2017, https://doi.org/10.26868/25222708.2017.192.
[76] J. Liu, X. Xie, F. Qin, S. Song, D. Lv, A case study of ground source direct cooling system integrated with water storage tank system, Build. Simulat. 9 (6) (2016) 659–668, https://doi.org/10.1007/s12273-016-0297-0.
[77] Q. Hassan, S. Algburi, A.Z. Sameen, H.M. Salman, M. Jaszczur, A review of hybrid renewable energy systems: solar and wind-powered solutions: challenges, opportunities, and policy implications, Results in Engineering 20 (2023) 101621, https://doi.org/10.1016/j.rineng.2023.101621.
[78] G. Leroux, N. Le Pierrès, L. Stephan, E. Wurtz, J. Anger, L. Mora, Pilot-scale experimental study of an innovative low-energy and low-cost cooling system for buildings, Appl. Therm. Eng. 157 (2019) 113665, https://doi.org/10.1016/j.applthermaleng.2019.04.075.
[79] S.-H. Yoo, Thermal behavior of passive intelligent radiant cooling systems, Processes 10 (12) (2022) 2666, https://doi.org/10.3390/pr10122666.
[80] J.-M. Seo, D. Song, K.H. Lee, Possibility of coupling outdoor air cooling and radiant floor cooling under hot and humid climate conditions, Energy Build. 81 (2014) 219–226, https://doi.org/10.1016/j.enbuild.2014.06.023.
[81] M. Schmelas, T. Feldmann, E. Bollin, Savings through the use of adaptive predictive control of thermo-active building systems (TABS): a case study, Appl. Energy 199 (2017) 294–309, https://doi.org/10.1016/j.apenergy.2017.05.032.
[82] Q. Kong, J. Feng, C. Yang, Z. Miao, X. He, Numerical simulation of a radiant floor cooling office based on CFD-BES coupling and FEM, Energy Proc. 105 (2017) 3577–3583, https://doi.org/10.1016/j.egypro.2017.03.825.
[83] L. Zhang, X. Liu, K. Zhao, Y. Jiang, Entransy analysis and application of a novel indoor cooling system in a large space building, Int. J. Heat Mass Tran. 85 (2015) 228–238, https://doi.org/10.1016/j.ijheatmasstransfer.2015.01.057.
[84] X. Zhu, J. Liu, X. Zhu, X. Wang, Y. Du, J. Miao, Experimental study on operating characteristic of a combined radiant floor and fan coil cooling system in a high humidity environment, Buildings 12 (4) (2022) 499, https://doi.org/10.3390/buildings12040499.
[85] Sholahudin Nasruddin, P. Satrio, T.M.I. Mahlia, N. Giannetti, K. Saito, Optimization of HVAC system energy consumption in a building using artificial neural network and multi-objective genetic algorithm, Sustain. Energy Technol. Assessments 35 (2019) 48–57, https://doi.org/10.1016/j.seta.2019.06.002.
[86] S. Cheng, Z. Chen, Study on indoor comfort of floor radiant cooling and displacement ventilation system in large space, proceedings of the IOP Conference Series: Earth and Environmental Science (2019), https://doi.org/10.1088/1755-1315/238/1/012078.
[87] J.M. Cejudo López, F.F. Hernández, F.D. Muñoz, A.C. Andrés, The optimization of the operation of a solar desiccant air handling unit coupled with a radiant floor, Energy Build. 62 (2013) 427–435, https://doi.org/10.1016/j.enbuild.2013.03.030.
[88] F. Ge, C. Wang, Exergy analysis of dehumidification systems: a comparison between the condensing dehumidification and the desiccant wheel dehumidification, Energy Convers. Manag. 224 (2020) 113343, https://doi.org/10.1016/j.enconman.2020.113343.
[89] E.Z.E. Conceição, M.M.J.R. Lúcio, H.B. Awbi, Comfort and airflow evaluation in spaces equipped with mixing ventilation and cold radiant floor, Build. Simulat. 6 (1) (2013) 51–67, https://doi.org/10.1007/s12273-012-0093-4.
[90] S. Liying, T. Shuang, Z. Lujie, Working parameter selection and analysis of radiant floor cooling combined with desk-based task/ambient conditioning (TAC) system, Build. Serv. Eng. Res. T. 38 (1) (2016) 104–120, https://doi.org/10.1177/0143624416669831.
[91] D. Zhang, N. Cai, Y. Rui, H. Tang, M. Liu, Experimental study on performance comparison between heavy and lightweight radiant floor cooling combined with underfloor ventilation air conditioning system. Proceedings of the 8th International Symposium on Heating, Ventilation and Air Conditioning, Berlin (Heidelberg), 2014.
[92] X. Xia, X. Zhang, Experimental study on performance of lightweight radiant floor cooling combined with underfloor ventilation system. Low-carbon City and New-type Urbanization, Springer Berlin Heidelberg, Berlin (Heidelberg), 2015, pp. 307–315.
[93] A. Fernández-Gutiérrez, I. González-Prieto, L. Parras, J.M. Cejudo-López, C. Del Pino, Experimental and numerical study of a small-scale and low-velocity indoor diffuser coupled with radiant floor cooling, Int. J. Heat Mass Tran. 87 (2015) 71–78, https://doi.org/10.1016/j.ijheatmasstransfer.2015.03.068.
[94] F. Causone, F. Baldin, B.W. Olesen, S.P. Corgnati, Floor heating and cooling combined with displacement ventilation: possibilities and limitations, Energy Build. 42 (12) (2010) 2338–2352, https://doi.org/10.1016/j.enbuild.2010.08.001.
[95] M. Krajčík, R. Tomasi, A. Simone, B.W. Olesen, Experimental study including subjective evaluations of mixing and displacement ventilation combined with radiant floor heating/cooling system, HVAC R Res. 19 (8) (2013) 1063–1072, https://doi.org/10.1080/10789669.2013.806173.
[96] L. Schellen, M.G.L.C. Loomans, M.H. De Wit, B.W. Olesen, W.D.V.M. Lichtenbelt, Effects of different cooling principles on thermal sensation and physiological responses, Energy Build. 62 (2013) 116–125, https://doi.org/10.1016/j.enbuild.2013.01.007.
[97] J. Liu, Z. Li, M.K. Kim, S. Zhu, L. Zhang, J. Srebric, A comparison of the thermal comfort performances of a radiation floor cooling system when combined with a range of ventilation systems, Indoor Built, Environ. Times 29 (4) (2019) 527–542, https://doi.org/10.1177/1420326X19869412.
[98] M. Krajčík, A. Simone, R. Tomasi, B.W. Olesen, Radiant floor cooling combined with mixing ventilation in a residential room: thermal comfort and ventilation effectiveness. Proceedings of the 11th REHVA World Congress & 8th International Conference on IAQVEC, Prague (Czech Republic), 2013.
[99] S. Liying, T. Shuang, Z. Lujie, Working parameter selection and analysis of radiant floor cooling combined with desk-based task/ambient conditioning (TAC), System 38 (1) (2017) 104–120, https://doi.org/10.1177/0143624416669831.
[100] B. Halvoňová, A.K. Melikov, Performance of "ductless" personalized ventilation in conjunction with displacement ventilation: impact of intake height, Build. Environ. 45 (4) (2010) 996–1005, https://doi.org/10.1016/j.buildenv.2009.10.007.
[101] J. Liu, D.A. Dalgo, S. Zhu, H. Li, L. Zhang, J. Srebric, Performance analysis of a ductless personalized ventilation combined with radiant floor cooling system and displacement ventilation, Build. Simulat. 12 (5) (2019) 905–919, https://doi.org/10.1007/s12273-019-0521-9.
[102] N. Cai, D. Zhang, An experimental study on operating characteristic of radiant floor cooling integrated with underfloor ventilation system, Int. J. Heat. Technol. 39 (4) (2021) 1207–1212, https://doi.org/10.18280/ijht.390418.
[103] F. Fernández Hernández, J.M. Cejudo López, A. Fernández Gutiérrez, F. Domínguez Muñoz, A new terminal unit combining a radiant floor with an underfloor air system: experimentation and numerical model, Energy Build. 133 (2016) 70–78, https://doi.org/10.1016/j.enbuild.2016.09.040.
[104] E. Nemethova, M. Krajcik, D. Petras, Performance of the building with three different radiant systems, MSE 471 (6) (2019) 062013, https://doi.org/10.1088/1757-899X/471/6/062013.
[105] B.W. Olesen, Operation and control of thermally activated slab heating and cooling systems. Proceedings of the the 6th International Conference on Indoor Air Quality, Ventilation & Energy Conservation in Buildings IAQVEC 2007, Sendai (Japan), 2007.
[106] Y. Yang, Y. Wang, X. Yuan, Y. Zhu, D. Zhang, Simulation study on the thermal environment in an office with radiant cooling and displacement ventilation system, Procedia Eng. 205 (2017) 3146–3153, https://doi.org/10.1016/j.proeng.2017.10.142.
[107] B. Zhuang, J. Shi, Z. Chen, Numerical study on indoor environment and thermal comfort in train station waiting hall with two different air-conditioning modes, Build. Simulat. 14 (2) (2021) 337–349, https://doi.org/10.1007/s12273-020-0732-0.
[108] H. Tang, X.-H. Liu, Y. Jiang, Theoretical and experimental study of condensation rates on radiant cooling surfaces in humid air, Build. Environ. 97 (2016) 1–10, https://doi.org/10.1016/j.buildenv.2015.12.003.
[109] S. Taheri, P. Hosseini, A. Razban, Model predictive control of heating, ventilation, and air conditioning (HVAC) systems: a state-of-the-art review, J. Build. Eng. 60 (2022) 105067, https://doi.org/10.1016/j.jobe.2022.105067.
[110] A. Afram, F. Janabi-Sharifi, Theory and applications of HVAC control systems – a review of model predictive control (MPC), Build. Environ. 72 (2014) 343–355, https://doi.org/10.1016/j.buildenv.2013.11.016.
[111] E. Bourdakis, O.B. Kazanci, B.W. Olesen, Load calculations of radiant cooling systems for sizing the plant, Energy Proc. 78 (2015) 2639–2644, https://doi.org/10.1016/j.egypro.2015.11.333.
[112] J. Joe, P. Karava, X. Hou, J. Hu, Model predictive control of a radiant floor cooling system in an office space. Proceedings of the 4th International High Performance Buildings Conference at Purdue, West Lafayette (United States), 2016.
[113] M. Gwerder, B. Lehmann, J. Tödtli, V. Dorer, F. Renggli, Control of thermally-activated building systems (TABS), Appl. Energy 85 (7) (2008) 565–581, https://doi.org/10.1016/j.apenergy.2007.08.001.
[114] M. Gwerder, J. Todtli, B. Lehmann, V. Dorer, W. Guntensperger, F. Renggli, Control of thermally activated building systems (TABS) in intermittent operation with pulse width modulation, Appl. Energy 86 (9) (2009) 1606–1616, https://doi.org/10.1016/j.apenergy.2009.01.008.
[115] A. Arteconi, D. Costola, P. Hoes, J.L.M. Hensen, Analysis of control strategies for thermally activated building systems under demand side management mechanisms, Energy Build. 80 (2014) 384–393, https://doi.org/10.1016/j.enbuild.2014.05.053.
[116] G. Sastry, P. Rumsey, VAV vs. radiant: side-by-side comparison, ASHRAE J. 56 (5) (2014) 16–24.
[117] Y. Khan, V.R. Khare, J. Mathur, M. Bhandari, Performance evaluation of radiant cooling system integrated with air system under different operational strategies, Energy Build. 97 (2015) 118–128, https://doi.org/10.1016/j.enbuild.2015.03.030.
[118] H. Jia, X. Pang, P.J.a.E. Haves, Experimentally-determined characteristics of radiant systems for office buildings, Appl. Energy 221 (2018) 41–54, https://doi.org/10.1016/j.apenergy.2018.03.121.
[119] H. Tang, P. Raftery, X. Liu, S. Schiavon, J. Woolley, F.S. Bauman, Performance analysis of pulsed flow control method for radiant slab system, Build. Environ. 127 (2018) 107–119, https://doi.org/10.1016/j.buildenv.2017.11.004.
[120] J. Joe, P. Karava, X. Hou, Y. Xiao, J. Hu, A distributed approach to model-predictive control of radiant comfort delivery systems in office spaces with localized thermal environments, Energy Build. 175 (2018) 173–188, https://doi.org/10.1016/j.enbuild.2018.06.068.
[121] D.L. Zhang, N. Cai, X.B. Cui, X.Y. Xia, J.Z. Shi, X.Q. Huang, Experimental investigation on model predictive control of radiant floor cooling combined with underfloor ventilation system, ENERGY 176 (2019) 23–33, https://doi.org/10.1016/j.energy.2019.03.102.
[122] J. Joe, P. Karava, A model predictive control strategy to optimize the performance of radiant floor heating and cooling systems in office buildings, Appl. Energy 245 (2019) 65–77, https://doi.org/10.1016/j.apenergy.2019.03.209.

[123] J. Drgoňa, D. Picard, L. Helsen, Cloud-based implementation of white-box model predictive control for a GEOTABS office building: a field test demonstration, J. Process Control 88 (2020) 63–77, https://doi.org/10.1016/j.jprocont.2020.02.007.
[124] X. Wang, W. Lei, W. Zhang, Y. Zhang, L. Zhang, Simplified calculation and control method of floor surface temperature for radiant floor and fresh air coupled cooling systems in steady-state, Case Stud. Therm. Eng. 27 (2021) 101320, https://doi.org/10.1016/j.csite.2021.101320.
[125] T. Arghand, S. Javed, A. Trüschel, J.-O. Dalenbäck, A comparative study on borehole heat exchanger size for direct ground coupled cooling systems using active chilled beams and TABS, Energy Build. 240 (2021) 110874, https://doi.org/10.1016/j.enbuild.2021.110874.
[126] Y. Hu, X. Xia, J. Wang, Research on operation strategy of radiant cooling system based on intermittent operation characteristics, J. Build. Eng. 45 (2022) 103483, https://doi.org/10.1016/j.jobe.2021.103483.
[127] M. Cui, J. Liu, M.K. Kim, X. Wu, Application potential analysis of different control strategies for radiant floor cooling systems in office buildings in different climate zones of China, Energy Build. 282 (2023) 112772, https://doi.org/10.1016/j.enbuild.2023.112772.
[128] X. Wang, T. Mu, L. Zhang, W. Zhang, L. Zhang, A simplified thermal comfort calculation method of radiant floor cooling technology for office buildings in northern China, Buildings 12 (4) (2022) 483, https://doi.org/10.3390/buildings12040483.
[129] C. Mayr, PID Controller Design, Stability Analysis and Controller Design of Local Model Networks, Springer Fachmedien Wiesbaden, Wiesbaden (Germany), 2021, pp. 69–97, https://doi.org/10.1007/978-3-658-34008-7_5.
[130] J. Clauß, S. Stinner, I. Sartori, L. Georges, Predictive rule-based control to activate the energy flexibility of Norwegian residential buildings: case of an air-source heat pump and direct electric heating, Appl. Energy 237 (2019) 500–518, https://doi.org/10.1016/j.apenergy.2018.12.074.
[131] M. Krzaczek, Z. Kowalczuk, Gain Scheduling Control applied to Thermal Barrier in systems of indirect passive heating and cooling of buildings, Control Eng. Pract. 20 (12) (2012) 1325–1336, https://doi.org/10.1016/j.conengprac.2012.07.007.
[132] W.J. Rugh, J.S. Shamma, Research on gain scheduling, Automatica 36 (10) (2000) 1401–1425, https://doi.org/10.1016/S0005-1098(00)00058-3.
[133] J. Romaní, A. De Gracia, L.F. Cabeza, Simulation and control of thermally activated building systems (TABS), Energy Build. 127 (2016) 22–42, https://doi.org/10.1016/j.enbuild.2016.05.057.
[134] T. Zakula, P.R. Armstrong, L. Norford, Modeling environment for model predictive control of buildings, Energy Build. 85 (2014) 549–559, https://doi.org/10.1016/j.enbuild.2014.09.039.
[135] A.S. Derakhtenjani, A.K. Athienitis, A frequency domain transfer function methodology for thermal characterization and design for energy flexibility of zones with radiant systems, Renew. Energy 163 (2021) 1033–1045, https://doi.org/10.1016/j.renene.2020.06.131.
[136] M. Su, J. Liu, M.K. Kim, X. Wu, Predicting moisture condensation risk on the radiant cooling floor of an office using integration of a genetic algorithm-back-propagation neural network with sensitivity analysis, Energy and Built Environment 5 (1) (2022) 110–129, https://doi.org/10.1016/j.enbenv.2022.08.004.
[137] D. Joshi, Genetic algorithm and its applications - a brief study, Asian Journal of Convergence in Technology. 7 (3) (2021) 8–12, https://doi.org/10.33130/AJCT.2021v07i03.002.
[138] P. Fogarty, Fuzzy logic, a logician's perspective. Fuzzy Logic: Recent Applications and Developments, Springer International Publishing., Cham (Switzerland), 2021, pp. 1–9, https://doi.org/10.1007/978-3-030-66474-9_1.
[139] Y. Liang, T.-P. He, Survey on soft computing, Soft Comput. 24 (2) (2020) 761–770, https://doi.org/10.1007/s00500-019-04508-z.
[140] F. Qin, C. Wang, L. Feng, H. Lv, Modeling based on semi-tensor product for radiant floor cooling systems, Procedia Eng. 205 (2017) 3782–3788, https://doi.org/10.1016/j.proeng.2017.10.137.
[141] M. Schmelas, T. Feldmann, P. Wellnitz, E. Bollin, Adaptive predictive control of thermo-active building systems (TABS) based on a multiple regression algorithm: first practical test, Energy Build. 129 (2016) 367–377, https://doi.org/10.1016/j.enbuild.2016.08.013.
[142] Y. Yao, D.K. Shekhar, State of the art review on model predictive control (MPC) in Heating Ventilation and Air-conditioning (HVAC) field, Build. Environ. 200 (2021) 107952, https://doi.org/10.1016/j.buildenv.2021.107952.
[143] N.T. Gayeski, P.R. Armstrong, L.K. Norford, Predictive pre-cooling of thermo-active building systems with low-lift chillers, HVAC R Res. 18 (5) (2012) 858–873, https://doi.org/10.1080/10789669.2012.643752.
[144] Z. Kang, X. Peng, X. Cheng, G. Feng, Analysis of condensation and thermal comfort of two kinds of compound radiant cooling air conditioning systems based on displacement ventilation, Procedia Eng. 205 (2017) 1529–1534, https://doi.org/10.1016/j.proeng.2017.10.233.
[145] C.-H. Jeong, M.-S. Yeo, K.-W. Kim, Feasibility of a radiant floor cooling system for residential buildings with massive concrete slab in a hot and humid climate, INT. J. CONCR. STRUCT. M. 12 (1) (2018) 80, https://doi.org/10.1186/s40069-018-0314-z.
[146] S. Oxizidis, A.M. Papadopoulos, Performance of radiant cooling surfaces with respect to energy consumption and thermal comfort, Energy Build. 57 (2013) 199–209, https://doi.org/10.1016/j.enbuild.2012.10.047.
[147] J.-H. Lim, M. Yeo, K.-W. Kim, A study on the application of the radiant floor cooling system integrated with a dehumidification system. Proceedings of the Eighth International IBPSA Conference, Eindhoven (Netherlands), 2003.
[148] Y.L. Yin, R. Wang, X. Zhai, T.F. Ishugah, Experimental investigation on the heat transfer performance and water condensation phenomenon of radiant cooling panels, Build. Environ. 71 (2014) 15–23, https://doi.org/10.1016/J.BUILDENV.2013.09.016.
[149] J.-H. Lim, Y.-Y. Kim, M. Yeo, K.-W. Kim, A comparative study on the control of the radiant floor cooling system. Proceedings of the Clima 2000 Naples 2001 Conference, Naples (Italy), 2001.
[150] M. Su, J. Liu, S. Zhou, J. Miao, M.K. Kim, Dynamic prediction of the pre-dehumidification of a radiant floor cooling and displacement ventilation system based on computational fluid dynamics and a back-propagation neural network: a case study of an office room, Indoor Built, Environ. Times 31 (10) (2022) 2386–2410, https://doi.org/10.1177/1420326X221107110.
[151] Ashrae, Measurement of Energy, Demand, and Water Saving, ASHRAE, Atlanta, 2014.
[152] X. Sui, X.S. Zhang, Xuemin, X. Zhang, Analysis on combinations of indoor thermal microclimate parameters in radiant cooled residential buildings and drawing of new thermal comfort charts, Build. Serv. Eng. Res. T. 37 (1) (2016) 66–84, https://doi.org/10.1177/0143624415596924.
[153] X. Sui, X. Zhang, Analysis on combinations of indoor thermal microclimate parameters in radiant cooled residential buildings and drawing of new thermal comfort charts, Build. Serv. Eng. Res. T. 37 (1) (2015) 66–84, https://doi.org/10.1177/0143624415596924.
[154] European Committee for Standardization, EN 16798-1:2019, Energy performance of buildings-Ventilation for buildings-Part 1: indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality. Thermal Environment, Lighting and Acous, 2019. Brussels.
[155] M. GB 55015-2021, General Code for Energy Efficiency and Renewable Energy Application in Buildings, China Construction Industry Press, Beijing, 2021 (in Chinese). OHURD.
[156] Q.J. Kwong, M.A. Arsad, N.M. Adam, Evaluation of indoor thermal environment in a radiant-cooled-floor office building in Malaysia, Appl. Mech. Mater. 564 (2014) 228–233, https://doi.org/10.4028/www.scientific.net/AMM.564.228.
[157] Y. Deng, Y. Ding, S. Chen, J. Li, C. Zhou, Study on radiant heat exchange between human body and radiant surfaces under asymmetric radiant cooling environments, Therm. Sci. Eng. Prog. 37 (2023) 101617, https://doi.org/10.1016/j.tsep.2022.101617.
[158] ISO, ISO 11855-1: 2021 (E), Building Environment Design — Embedded Radiant Heating and Cooling Systems — Part 1: Definitions, Symbols, and Comfort Criteria, International Standardization Organization, Switzerland, 2021.
[159] X. Zhou, Y. Liu, M. Luo, L. Zhang, Q. Zhang, X. Zhang, Thermal comfort under radiant asymmetries of floor cooling system in 2 h and 8 h exposure durations, Energy Build. 188–189 (2019) 98–110, https://doi.org/10.1016/j.enbuild.2019.02.009.
[160] S. Lu, M. Cui, B. Gao, J. Liu, J. Ni, J. Liu, S. Zhou, A comparative analysis of machine learning algorithms in predicting the performance of a combined radiant floor and fan coil cooling system, Buildings 14 (6) (2024) 1659, https://doi.org/10.3390/buildings14061659.
[161] X. Zhou, Y. Liu, J. Zhang, L. Ye, M. Luo, Radiant asymmetric thermal comfort evaluation for floor cooling system – a field study in office building, Energy Build. 260 (2022) 111917, https://doi.org/10.1016/j.enbuild.2022.111917.
[162] W. Liu, C. Liu, Y. Lin, L. Ma, K. Bai, Y. Wu, Optimal scheduling of residential microgrids considering virtual energy storage system, Energies 11 (4) (2018) 942, https://doi.org/10.3390/en11040942.
[163] R. Hu, X. Li, J. Liang, H. Wang, G. Liu, Field study on cooling performance of a heat recovery ground source heat pump system coupled with thermally activated building systems (TABSs), Energy Convers. Manag. 262 (2022) 115678, https://doi.org/10.1016/j.enconman.2022.115678.
[164] M.K. Kim, H. Leibundgut, J.-H. Choi, Energy and exergy analyses of advanced decentralized ventilation system compared with centralized cooling and air ventilation systems in the hot and humid climate, Energy Build. 79 (2014) 212–222, https://doi.org/10.1016/j.enbuild.2014.05.009.
[165] O.B. Kazanci, M. Shukuya, B.W. Olesen, Energy and exergy performances of air-based vs. Water-based heating and cooling systems: a case study of a single-family house. Proceedings of the in Proceedings of the 2016 ASHRAE Annual Conference, 2016.
[166] M. Shukuya, Exergy concept and its application to the built environment, Build. Environ. 44 (7) (2009) 1545–1550, https://doi.org/10.1016/j.buildenv.2008.06.019.
[167] H. Torío, D. Schmidt, Development of system concepts for improving the performance of a waste heat district heating network with exergy analysis, Energy Build. 42 (10) (2010) 1601–1609, https://doi.org/10.1016/j.enbuild.2010.04.002.
[168] D.E. Kalz, J. Wienold, M. Fischer, D. Cali, Novel heating and cooling concept employing rainwater cisterns and thermo-active building systems for a residential building, Appl. Energy 87 (2) (2010) 650–660, https://doi.org/10.1016/j.apenergy.2009.06.002.
[169] Z. Tian, J.A. Love, Energy performance optimization of radiant slab cooling using building simulation and field measurements, Energy Build. 41 (3) (2009) 320–330, https://doi.org/10.1016/j.enbuild.2008.10.002.
[170] J. Kolarik, J. Toftum, B.W. Olesen, Operative temperature drifts and occupant satisfaction with thermal environment in three office buildings using radiant heating/cooling system. Proceedings of the Healthy Buildings Europe 2015, 2015. Eindhoven (Netherlands).

[171] W. Casas, G. Schmitz, Experiences with a gas driven, desiccant assisted air conditioning system with geothermal energy for an office building, Energy Build. 37 (5) (2005) 493–501, https://doi.org/10.1016/j.enbuild.2004.09.011.
[172] M. Cellura, F. Guarino, S. Longo, M. Mistretta, Energy life-cycle approach in Net zero energy buildings balance: operation and embodied energy of an Italian case study, Energy Build. 72 (2014) 371–381, https://doi.org/10.1016/j.enbuild.2013.12.046.
[173] O. Berk Kazancı, Beyond nZEB: experimental investigation of the thermal indoor environment and energy performance of a single-family house designed for plus-energy targets, Sci. Technol. Built. Environ. 22 (7) (2016) 1023–1038.
[174] D. Lehrer, Nine Radiant Case Study Buildings Demonstrate Energy Efficiency and Occupant Satisfaction, Center for the Built Envieonment, New Buildings Institute, TRC Energy Services, 2017. https://cbe.berkeley.edu/centerline/nine-radiant-buildings-demonstrate-energy-efficiency-and-occupant-satisfaction/.
[175] J. Liu, M. Cui, X. Xie, S. Zhou, S. Song, P. Cui, 16 - application of the radiant floor cooling system with direct-ground cooling source and displacement ventilation in an office building in Jinan, Shandong Province, China. Air Conditioning with Natural Energy, Elsevier., 2024, pp. 343–352, https://doi.org/10.1016/B978-0-443-13506-4.00006-1.
[176] J.Ü. Pfafferott, S. Herkel, D.E. Kalz, A. Zeuschner, Comparison of low-energy office buildings in summer using different thermal comfort criteria, Energy Build. 39 (7) (2007) 750–757, https://doi.org/10.1016/j.enbuild.2007.02.005.
[177] Y. Li, F. Niu, D. Qian, O.N. Zheng, Nationwide energy saving analysis of radiant floor system for commercial buildings. Proceedings of the 2018 ASHRAE Annual Conference, Houston (United States), 2018.
[178] A. Odyjas, A. Górka, Simulations of floor cooling system capacity, Appl. Therm. Eng. 51 (1) (2013) 84–90, https://doi.org/10.1016/j.applthermaleng.2012.08.029.
[179] K. Zhao, G. Lv, C. Shen, J. Ge, Investigating the effect of solar heat gain on intermittent operation characteristics of radiant cooling floor, Energy Build. 255 (2022) 111628, https://doi.org/10.1016/j.enbuild.2021.111628.
[180] J. Liu, J. Ren, L. Zhang, X. Xie, M.K. Kim, L. Zhang, Optimization of control strategies for the radiant floor cooling system combined with displacement ventilation: a case study of an office building in jinan, China, J. Archit. Eng. 6 (2019) 33–48, https://doi.org/10.15377/2409-9821.2019.06.5.
[181] D. Liu, H. Zhou, A. Hu, Q. Zhang, N. Liu, J. Wen, Study on the intermittent operation mode characteristic of a convection-radiation combined cooling system in office buildings, Energy Build. 255 (2022) 111669, https://doi.org/10.1016/j.enbuild.2021.111669.
[182] V. Echarri-Iribarren, Conditioning using ceramic floor panels with capillary tube mats and solar thermal panels on the Mediterranean coast: energy savings and investment amortisation, Energy Build. 202 (2019) 109334, https://doi.org/10.1016/j.enbuild.2019.109334.
[183] W. Kessling, S. Holst, M. Schuler, Innovative design concept for the new bangkok international airport, NBIA, proceedings of the Fourteenth Symposium on Improving Building Systems in Hot and Humid Climates (2004). Texas (United States), https://hdl.handle.net/1969.1/4628.
[184] Q.J. Kwong, S.J. Kho, J. Abdullah, V.R. Raghavan, Evaluation of energy conservation potential and complete cost-benefit analysis of the slab-integrated radiant cooling system: a Malaysian case study, Energy Build. 138 (2017) 165–174, https://doi.org/10.1016/j.enbuild.2016.12.014.
[185] D. Saelens, W. Parys, R. Baetens, Energy and comfort performance of thermally activated building systems including occupant behavior, Build. Environ. 46 (4) (2011) 835–848, https://doi.org/10.1016/j.buildenv.2010.10.012.
[186] A. Abdeen, E. Mushtaha, A. Hussien, C. Ghenai, A. Maksoud, V. Belpoliti, Simulation-based multi-objective genetic optimization for promoting energy efficiency and thermal comfort in existing buildings of hot climate, Results in Engineering 21 (2024) 101815, https://doi.org/10.1016/j.rineng.2024.101815.
[187] P. Ma, L.-S. Wang, N. Guo, Modeling of TABS-based thermally manageable buildings in Simulink, Appl. Energy 104 (2013) 791–800, https://doi.org/10.1016/j.apenergy.2012.12.006.
[188] J.J. Feng, S. Schiavon, F. Bauman, New method for the design of radiant floor cooling systems with solar radiation, Energy Build. 125 (2016) 9–18, https://doi.org/10.1016/j.enbuild.2016.04.048.
[189] A. Cacabelos, P. Eguía, L. Febrero, E. Granada, Development of a new multi-stage building energy model calibration methodology and validation in a public library, Energy Build. 146 (2017) 182–199, https://doi.org/10.1016/j.enbuild.2017.04.071.
[190] S. Dahal, Fault detection and diagnostic method based on evolving data-driven model for radiant heating and cooling systems. Proceedings of the 7th International High Performance Buildings Conference at Purdue, Indiana, United States, 2022.
[191] A. Hauashdh, S. Nagapan, J. Jailani, Y. Gamil, An integrated framework for sustainable and efficient building maintenance operations aligning with climate change, SDGs, and emerging technology, Results in Engineering 21 (2024) 101822, https://doi.org/10.1016/j.rineng.2024.101822.
[192] K. Du, H. Wu, G. Huang, X. Xu, Y. Liu, Condensation-free radiant cooling with double-skin infrared-transparent membranes, Build. Environ. 193 (2021) 107660, https://doi.org/10.1016/j.buildenv.2021.107660.
[193] Y. Liang, N. Zhang, H. Wu, X. Xu, K. Du, J. Yang, Q. Sun, K. Dong, G. Huang, Thermal environment and thermal comfort built by decoupled radiant cooling units with low radiant cooling temperature, Build. Environ. 206 (2021) 108342, https://doi.org/10.1016/j.buildenv.2021.108342.
[194] Y. Boutahri, A. Tilioua, Machine learning-based predictive model for thermal comfort and energy optimization in smart buildings, Results in Engineering 22 (2024) 102148, https://doi.org/10.1016/j.rineng.2024.102148.
[195] S. Qureshi, R.A. Memon, A.G. Memon, A four-step method based on sequential solution of relevant model equations to predict condensation risk for a radiant cooling system, J. Build. Eng. 64 (2023) 105601, https://doi.org/10.1016/j.jobe.2022.105601.
[196] B. Olesen, Radiant floor cooling systems, ASHRAE J. 50 (9) (2008) 16–22.
[197] H. Begić, H. Krstić, Comprehensive review and comparative analysis of building condition assessment models, Results in Engineering 22 (2024) 102176, https://doi.org/10.1016/j.rineng.2024.102176.