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Invited Review Article

Condensation prevention strategies in radiant cooling systems: A comprehensive review

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ABSTRACT

Radiant cooling technology is an energy-efficient alternative to the conventional air conditioning system. Condensation risk is one of the challenges hindering the application of radiant cooling systems, especially in hot and humid areas. Condensate water on radiant cooling terminals would cause adverse effects on indoor environment quality and damage building materials and assemblies. Attention has been given to condensation prevention for radiant cooling systems from early engineering practices to the latest research, but its advances have not yet been systematically reviewed and discussed. Hence, this article reviews the state-of-the-art research on condensation prevention as well as the anti-condensation strategies applied in engineering practices. The condensation prevention strategies regarding humidity control and temperature control are summarized and discussed in terms of dehumidification approaches, indoor humidity control strategies, factors influencing the surface temperature of radiant cooling terminals and the relevant temperature control strategies for condensation prevention. Research on condensation-free radiant cooling technologies are reviewed and analyzed based on their innovative system configurations. In addition, the advances in the condensation-managed radiant cooling terminals that allows surface condensation are discussed. Finally, condensation prevention considerations in design guidelines and engineering cases are summarized and comparatively analyzed. According to the review, it is deduced that condensation issue can be addressed by proper design and operation but condensation prevention strategies may fail due to unpredictable human behaviors and device fault. The novel condensation-free and condensation-managed radiant cooling terminals substantially mitigate condensation risks, yet their applicability in buildings still needs improvement. This review is expected to provide valuable insights and references for researchers and engineers engaged in the research, design, and operation of radiant cooling systems.

1. Introduction

Demands for space cooling may continue to increase [1] due to more frequent and intensive heat exposures [2] burgeoning with potentially accelerating global warming [3]. As one of the alternatives to all air-conditioning systems, radiant cooling systems are gaining attention in both academia and industry market due to its energy saving potential and good thermal comfort level. Radiant cooling systems are generally characterized as that thermal radiation contributes more than half of its total heat extraction [4]. The radiant cooling systems can be categorized into radiant cooling panels, embedded system, and thermally active building systems (TABS), based on their thermal mass [5]. Typically, a radiant cooling system can only handle the indoor sensible load, thus additional ventilation system should be combined to remove latent heat and meet ventilation requirements [6].

Condensation risk is one of the challenges hindering the widespread application of radiant cooling systems. It is believed that condensation caused the failure of early practices of the radiant cooling system developed in the 1930 s [7]. According to a recent survey of engineers, humidity control and condensation are the second greatest difficulty after high initial cost in the design of radiant cooling systems [8]. Condensation occurs when the radiant surface temperature falls below the dew point temperature of adjacent moist air. At the first stage, water vapor molecules move from the bulk humid air to the boundary layer,

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overcome the energy barrier, and form droplets via heterogeneous nucleation. The later individual droplets growth leads to coalescence with each other and finally form condensate water on the surface [9]. The morphology of the condensate, which is usually described as filmwise or dropwise, depends on the wettability and contact line dynamics of the surface. On the common radiant cooling surfaces which are typically hydrophilic, continuous liquid film tends to form due to the limited mobility of droplets and consequently covers the entire surface as condensation progresses [10]. The rate of condensation is affected by the temperature difference between the surface and space dew point, as well as the mass transfer rate of water vapor onto the surface [11]. The adverse effects on indoor environment quality and degradation of building materials caused by condensation water includes but not limited to (1) annoying dripping problems, (2) growth of mold on surfaces and porous building materials, (3) corrosion of metals, (4) decay or even rotting of wooden floors, (5) decrease of thermal resistance of building materials [12].

To prevent condensation in radiant cooling systems, effective monitoring and control of both indoor humidity and radiant surface temperature are indispensable. Typically, a dehumidification system is integrated with radiant cooling systems to remove moisture from indoor spaces, while the radiant surface temperature must be strictly controlled above the indoor air dew point to prevent condensation. However, this condensation control requirement reduces the heat exchange temperature difference between radiant cooling surfaces and indoor environments, which in turn limits the cooling capacity of radiant terminals. This limitation has become a great concern for engineers when designing a radiant cooling system in hot and humid areas, where sensible and latent cooling loads are large.

In recent decades, some successfully practices have been implemented in humid areas [13] and large-scale applications [14] based on a deeper understanding of the system design and operation principles. The two core considerations for the design of radiant cooling system, including heat transfer [15] and thermal comfort [16], have been extensively investigated and comprehensively documented in existing studies and reviews. However, condensation prevention as a key factor directly influencing the primary decision of a radiant cooling system, has merely been mentioned as a peripheral component in existing review articles [4,17–19] that primarily focus on overall system performance, heat transfer, or thermal comfort, rather than being systematically summarized, or synthesized, or analyzed in depth. Although a dedicated critical review [20] addressed passive condensation prevention technologies, condensation prevention as an independent and critical research theme still lacks a comprehensive and systematic review despite its role as a major challenge hindering the widespread application of radiant cooling technology.

To consolidate the fragmented research findings on condensation prevention as well as to address the lack of synthesized guidance for condensation-related challenges in practice, this article conducts a targeted and in-depth review of research articles and technical reports related to condensation prevention in radiant cooling systems. The article has a framework (Fig. 1) specified on following key aspects: (1) the integration of dehumidification ventilation system to enhance indoor humidity control and mitigate condensation risks; (2) the strategies of hydronic system control to avoid surface condensation while balancing cooling capacity; (3) the latest innovations of condensation-free radiant cooling terminals; (4) the advancements of condensation-managed terminals that allows surface condensation; (5) current considerations of condensation prevention in engineering applications. By organizing and clarifying the current status and future directions of condensation prevention technologies, this article provides a comprehensive framework for understanding condensation prevention strategies to overcome the bottleneck that limits the application of radiant cooling systems. It can be helpful for researchers and engineers engaged in the research, design, installation, and operation of radiant cooling systems.

2. Review method

Articles were collected by searching terms of “radiant cooling” and “condensation” in the scientific databases of ScienceDirect, Web of Science, and Wiley Online Library. Since condensation is a common issue widely discussed in the area of radiant cooling, the selection of reviewed articles was determined by their relevance to the topic of this review. Relevant articles not covered by those databases (like conference papers and technical reports) were searched in Google Scholar and eScholarship. Standards, design guidelines, and handbooks were reviewed to examine the opinion for engineering application. In addition, relevant publications found through references and citations were also reviewed. The source of research articles mainly includes Energy and Buildings, ASHRAE Journal, ASHRAE Transactions, Building and Environment, Applied Thermal Engineering, and Journal of Building Engineering.

3. Condensation prevention strategies for indoor humidity control

Indoor humidity levels have significant impacts on thermal comfort,

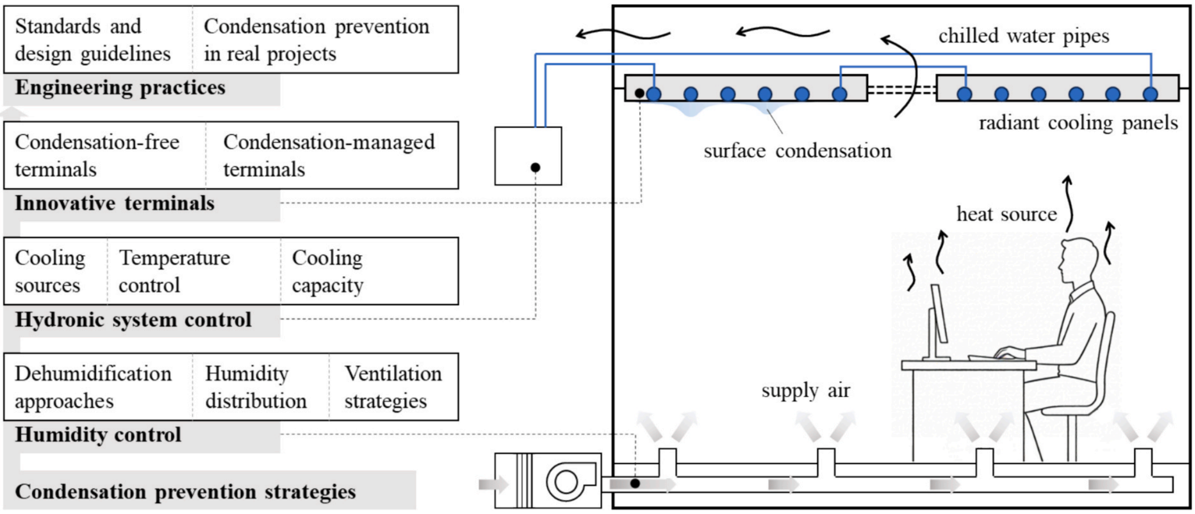

Fig. 1. Condensation prevention strategies-centered framework of the review.

indoor air quality, and health of materials and assemblies in buildings. Hence, the primary target of humidity control is to meet the requirements for sustaining a good indoor environment quality. However, implementing radiant cooling system imposes more stringent demands on humidity control for condensation prevention. This is usually achieved by an auxiliary dehumidification system.

The humidity ratio of indoor air can be influenced by many factors. Moisture can be transferred from outdoor air by ventilation and infiltration. Human activities like cooking and bathing can generate gaseous water into indoor spaces. Occupants are also a source of moisture, as vapor can be produced by metabolic processes such as respiration and perspiration. Indoor humidity varies based on the equilibrium of inflow and outflow of water vapor and the moisture buffering of hygroscopic materials in a room. Ventilation and occupant behaviors are the two main factors that dominates the change of indoor humidity [12]. If a building is naturally ventilated, the level of indoor humidity will be highly dependent on the outdoor air conditions. In humid areas, indoor humidity is maintained at the desired level by air dehumidification approaches such as cooling dehumidification and desiccant dehumidification. This part of review focuses on introducing the mainstream techniques used to provide indoor humidity control.

3.1. *Cooling dehumidification*

Cooling dehumidification is widely applied in air-conditioning systems. It employs cooling coil with circulated low-temperature chilled water or refrigerant to remove water vapor from the air stream through condensation and drainage. Shank and Mumma [21] suggested that dedicated outdoor air systems (DOAS) could be combined with ceiling radiant cooling panels to alleviate the condensation risks, and proposed a control algorithm for the combined system [22].

Cooling dehumidification can be integrated to make radiant cooling applicable in hot and humid areas. For instance, a combined high-temperature radiant cooling and decentralized dehumidification ventilation system was applied in Singapore [23], where three strategies for condensation prevention were emphasized: (1) supply air needed to be dehumidified to a low humidity ratio of less than 13 g/kg to mitigate condensation risk; (2) infiltration rate beyond one should be avoided to prevent the increment of humidity ratio; (3) air ventilation with high air flow rate rather than low air humidity was recommended to control indoor humidity for low exergy considerations. Saber et al. [24] used DOAS to keep the indoor air dew point in the range of 13–15°C to avoid condensation for radiant cooling panel applied in tropics.

The embedded radiant cooling systems can be combined with cooling dehumidification ventilation to realize condensation prevention. For instance, a combined cooling, dehumidification, ventilation, and radiant floor system was investigated [25]. A minimum dehumidification ventilation control was designed to prevent surface condensation on radiant floors. The key strategy was that the dehumidification coil was only operated when the temperature difference between the floor surface and the indoor air dew point is lower than a safety margin of 2°C. Song et al. [26] developed a control strategy of adjusting radiant floor supply water temperature according to outdoor temperature to improve thermal responsiveness and prevent condensation on radiant cooling floors.

3.2. *Desiccant dehumidification*

The principle of desiccant dehumidification is that water vapor is removed from air by adsorption or absorption due to the vapor pressure difference between the air and the desiccant surface when air stream passes through a liquid desiccant packing or a solid desiccant wheel. In the dehumidification process, the latent heat of water vapor is released, and the temperature of air stream will increase. Meanwhile, the vapor pressure of desiccants will also increase until reaching the equilibrium of the vapor pressure of the air. After that, the desiccants need to be regenerated and cooled to achieve continuous air dehumidification.

Dehumidification ventilation using liquid desiccants [27] and solid desiccants [28] can be combined with radiant cooling systems to prevent condensation. Niu et al. [29] first demonstrated that energy-saving and good indoor humidity control can be achieved by integrating desiccant dehumidification ventilation with ceiling cooling panel system in buildings. They found that more than 44% yearly primary energy consumption can be saved compared with a constant all-air system in Hong Kong [30]. The simulation work by Hao et al. [31] indicated an energy-saving of 8.2% by using a combined ceiling radiant cooling panel and desiccant dehumidification system in Beijing. For better control of indoor air humidity, energy-saving, and condensation prevention, model predictive control has been developed for a combined desiccant dehumidification ventilation and ceiling radiant cooling system [32,33].

Compared with cooling dehumidification, the desiccant dehumidification has advantages of energy saving by utilizing low-grade heat and avoiding over-cooling, though few studies provided comparative analysis on the energy consumption of radiant cooling combined with different dehumidification methods. Besides, the higher initial investment and more intensive space requirements for installing desiccant dehumidification systems hinders their application in engineering practices. Nevertheless, there are still several successful engineering cases in which desiccant dehumidification technologies have been applied for humidity control and condensation prevention in radiant cooling system, which will be further discussed in Section 7.2.

3.3. *Humidity control by outdoor air ventilation*

In temperate climates or transitional seasons, outdoor air with relatively low moisture content can be employed to help handle indoor latent loads as well as provide additional sensible cooling. Outdoor air can be supplied indoors by free operation of a mechanical ventilation system or by combining radiant cooling systems with natural ventilation. By this strategy, energy-saving can be achieved. Seo et al. [34] suggested that outdoor air cooling can be combined with radiant floor cooling to achieve more than 20% of energy-saving by the reduction of electricity consumption of chiller. An air ventilator was used to supply outdoor air and recirculate indoor air. To avoid condensation, a safety margin of 2°C between floor surface temperature and space dew point was set to activate the dehumidification coil. Bayoumi [35] found that the condensation risk could be avoid in winter and spring by hybrid natural ventilation and dehumidification for radiant cooling system in an education building. In humid summer and autumn, the condensation risk could be alleviated through improving the fraction of dehumidification ventilation in the hybrid ventilation.

3.4. *Impacts of humidity distribution*

When evaluating condensation risks for radiant cooling systems, it is often assumed that air is fully mixed and humidity is uniform in a room. However, water vapor pressure gradient exists due to non-uniformly distributed moisture sources, thermal plume around people, and air stratification. The non-uniformity of humidity in the buildings will cause difficulties for determining the position of humidity sensors used to monitor the space dew point when designing a system.

Humidity distribution in a room with radiant cooling systems is significantly affected by airflow. Analysis indicated that the humidity ratio in the ceiling area is higher than the occupied zone in a combined ceiling radiant cooling panel and displacement ventilation system (Fig. 2), while a uniform moisture distribution is more likely to be achieved in a combined ceiling radiant cooling and mixed ventilation system, therefore the surface temperature of combined chilled ceiling and displacement ventilation should be controlled at least 1°C higher than that of perfect mixing systems [36]. The types of air supply jets and air supply velocity can also affect the uniformity of spatial humidity distribution. It is suggested that linear air jets can provide more uniform

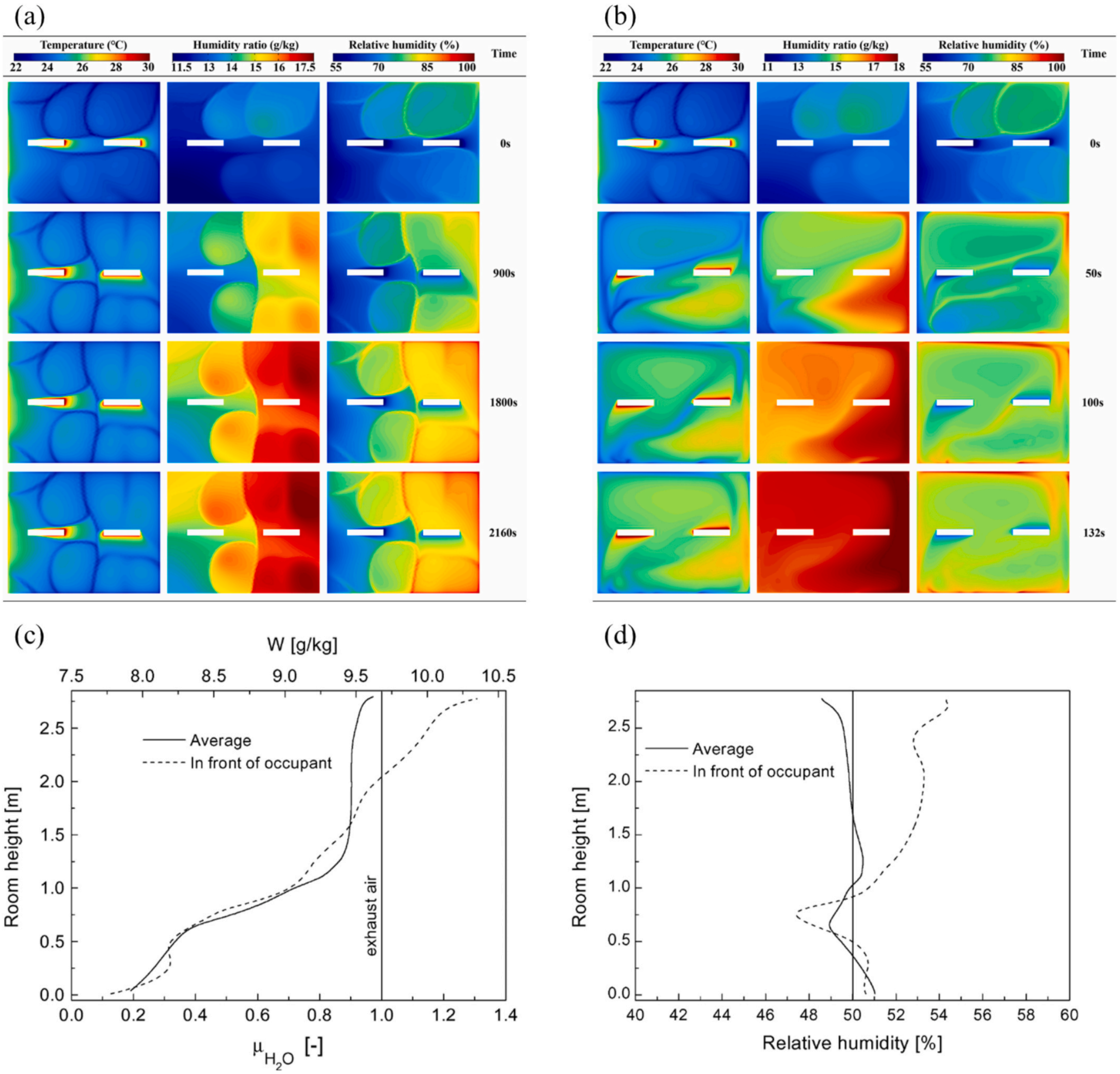

Fig. 2. Humidity distribution dynamics at ceiling panel surface (a) after increasing two occupants (near right side) and (b) after opening windows (at the left side) [39]. Copyright 2024, Elsevier. Vertical distribution of average and local (c) humidity ratio and (d) relative humidity in chilled ceiling and displacement ventilation system [36]. Copyright 2002, Elsevier.

moisture distribution and faster moisture removal in the start-up stage of fresh air supply in the attached layer [37]. Despite the air flow, the position of moisture sources and the distance between ceiling radiant cooling panels and moisture sources also have influences on the dynamic behavior of humidity [38]. Furthermore, Chen et al. [39] investigated the impact the increase of occupants and the opening of windows on the condensation risks of ceiling panels, and found that moisture spread along the airflow direction driven by thermal plume or outdoor air while condensation firstly occurred in the areas with the lowest temperature (Fig. 2).

3.5. Pre-dehumidification by ventilation

If a ventilation system is only operated during work time as typically seen in office buildings, humidity will increase gradually due to infiltration when the ventilation system is turned off. Indoor humidity ratio can approach the level of outdoor air after one night of moisture infiltration. To avoid condensation during the start-up stage, dehumidification ventilation should be operated first to lower the space dew point [43]. Zhang and Niu [44] suggested one-hour pre-dehumidification ventilation before starting radiant cooling systems to eliminate condensation risks when the air change rate of infiltration was 0.2 based on the hourly simulation of indoor humidity dynamics. If the building is well-sealed, the condensation risk can be significantly alleviated. Ge et al. [45] compared the time for pre-dehumidification under different infiltration air change rates and suggested 30 min for pre-dehumidification in buildings with combined chilled ceiling and DOAS in Hong Kong. Ren et al. [46] proposed that ventilation should be operated 1–1.5 h before work time to prevent condensation based on field measurement. Furthermore, Su et al. [47] evaluated the impacts of ventilation types, supply air flow rate, and supply air temperature on the time and energy consumption for pre-dehumidification in radiant cooling floor by an artificial neural network model. Their results indicated that displacement ventilation with high air flow rate can provide best pre-dehumidification effects compared with mixed ventilation and stratum ventilation. In addition to pre-dehumidification, Li et al. [48] proposed that synchronous start-up of the ventilation and radiant cooling system can be implemented by controlling the temperature drop rate of supply chilled water.

4. Condensation prevention strategies for hydronic system

The operation performance of hydronic system is the pivotal factor that affects the indoor thermal environment and the energy consumption of a radiant cooling system. The primary target of hydronic system control is to maintain the indoor temperature at the thermal comfort level while improving energy efficiency. This is also the main focus of substantial studies regarding the control of radiant cooling systems [49–52]. To prevent condensation, the temperature of a radiant surface must be kept higher than the space dew point. This part of review focuses on the condensation prevention strategies adopted in the control of hydronic system.

4.1. *Effects of cooling sources*

Two chilled water circuits with different temperatures are required in a combined cooling dehumidification and radiant cooling system, as the temperature for dehumidification (typically 7°C) is lower than that for radiant cooling (e.g. 16°C). This can be realized by using two separate chillers [30] or using one chiller and combined heat exchangers [42,53,54] to provide chilled water with different temperatures (Fig. 3).

When passive cooling techniques like evaporative cooling [55] is applied, the temperature of water that supplied to radiant cooling systems will be dependent on the temperature of cooling sources [41]. Vangtook et al. [56,57] proposed to use cooling tower to produce cooling water with a temperature of 24°C for radiant cooling panels in tropic areas. Though the cooling capacity was limited (lower than 40 W/m^2), condensation was successfully avoided as cooling water temperature is higher than the air dew point. The field test of a ground cooling-based radiant floor system indicated that ground cooling could provide chilled water with a temperature of 17-18°C, while indoor humidity ratio was reduced through ventilated air cooled and dehumidified by an auxiliary earth-air heat exchanger [58].

4.2. *Control of surface temperature*

The control of indoor operative temperature can be achieved by

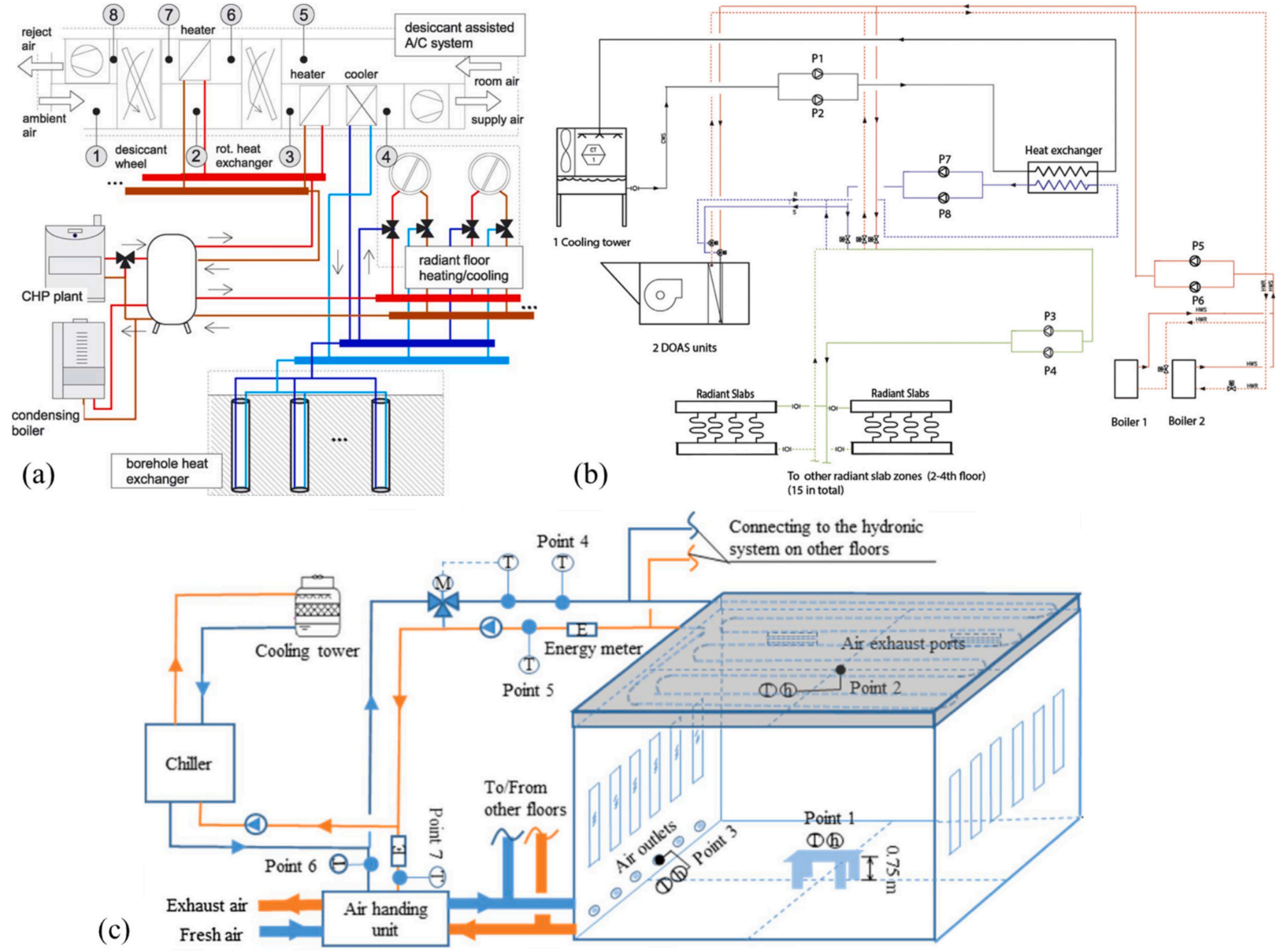

Fig. 3. Examples of hydronic systems with different cooling sources and dehumidification ventilation approaches in real projects. (a) Radiant cooling floor with geothermal energy and solid desiccant dehumidification [40]. Copyright 2005, Elsevier. (b) TABS with cooling tower and outdoor air ventilation [41]. Copyright 2014, Elsevier. (c) TABS with chiller and cooling dehumidification [42]. Copyright 2017, Elsevier.

either modulating chilled water flow rate or modulating chilled water temperature. However, Arghand et al. [59] suggested that chilled water temperature control method should be adopted to prevent condensation as the lowest supply temperature can be easily defined and controlled, while indoor air temperature was more stable compared with flow rate control as also pointed out by Lim et al. [60]. If the water flow rate control is applied for radiant cooling terminals, only the supply water turned off can the condensation be effectively prevented on the radiant surface [61].

Different control variables can be used for chilled water temperature control, including supply water temperature, mean temperature of supply and return water, and return water temperature. Babiak et al. [5] recommended modulating the mean temperature of supply and return chilled water for maintaining indoor thermal environments. For condensation prevention, the lowest supply water temperature can be controlled to be equal to the air dew point [62]. Since there is a temperature difference between chilled water and radiant surfaces due to thermal resistances, there will be no condensation risk on the surface.

If a radiant surface temperature is measured and used as the control variable, a margin of 1–2°C between the monitored temperature and the space dew point should be set to tolerate the disturbance of humidity variation and thermal response [4]. When the radiant surface temperature falls below the difference near the space dew point, the control algorithm will increase the supply chilled water temperature or directly turns off the water supply. If multiple panels are connected in serial, the surface temperature of the first panel connected to the main supply pipe should be monitored to prevent condensation. The considerations regarding the condensation prevention in the studies focused on the control of hydronic radiant cooling systems are summarized in Table 1.

The TABS has large thermal mass and slow response, making the time span for changing the condition of surface temperatures longer than other types of radiant cooling systems. To prevent condensation on the surface and inside the structure, a recommended approach is setting the lower limit for supply water temperature equal to the dew point [68]. In practice, the TABS is often operated in an intermittent duration of 8 h or 12 h and is cooled at night to take advantage of load shifting and achieve energy economics. Chung and Lim [67] pointed out that condensation risks would be increased in hot and humid areas because the surface temperature of TABS was maintained at 20–23°C all year round while infiltration of outdoor air would increase the indoor humidity at non-occupied period. They developed operation guidelines to avoid condensation based on the prediction of indoor dew point and the surface temperature of TABS. To avoid the condensation in the structure, Woo and Junghans [51] proposed a model predictive control (MPC) method to limit the volumetric moisture content of concrete structures less than the maximum hygroscopic level.

4.3. Effects of surface temperature uniformity

The non-uniformity of radiant cooling surface temperature may increase the risk of condensation. An infrared image indicated a temperature difference of 4°C could exist on a typical ceiling radiant cooling panel [69]. If the temperature sensor is not placed at the position with the lowest temperature, the panel surface temperature-based condensation prevention strategy may fail as condensation can occur in areas with a temperature lower than that measured by the sensor.

The temperature distribution on a radiant cooling panel is mainly affected by the placement of pipes and the thermal bonding between pipes and the surface. The temperature uniformity on a ceiling radiant cooling panel with different pipe connection methods was investigated in a study [69]. It was found that adding a thin air layer between pipes and panels helped create a uniform temperature distribution and reduce the maximum temperature and minimum temperature difference on the panel surface. Heat transfer between pipes and panels was dominated by thermal radiation between pipe surface and panel surface as well as heat conduction through the thin air layer. The heat transfer efficiency was sacrificed to improve temperature uniformity due to the increased thermal resistances between pipes and the panel surface, but the cooling capacity can be still improved when condensation prevention is considered. That is because the average panel surface temperature can be lower than that of conventional pipe connections.

4.4. Enhancement of cooling capacity

The control of condensation puts a limitation on the lowest temperature of a radiant panel, which in turn raises the concern of insufficient cooling capacity. If the cooling capacity can be enhanced with higher surface temperatures, condensation risks can be alleviated. A common enhancement approach is modifying the panel geometry, which has been summarized and discussed in a review article [70]. For instance, Wojkowiak et al. [71] developed a ceiling radiant cooling panel with a corrugated surface. Cooling capacity could be enhanced by 26% compared to conventional flat radiant cooling panels by the increased surface area and the augmented convective heat transfer coefficient. Ye et al. [72] proposed a ceiling radiant cooling panel with a segmented and concave surface. Their simulation showed that an optimum ventilation velocity of 0.164 m/s and ventilation air temperature of 25°C can be applied with a panel surface temperature as high as 23°C to provide better thermal comfort as well as to avoid condensation.

5. Condensation-free radiant cooling terminals

Some recently developed radiant cooling terminals can be operated

Table 1
Condensation prevention strategies in temperature control algorithms.

Study	System type	Control strategies	Modulated variable for indoor temperature control	Monitored variable for condensation prevention	Margin between the space dew point	Research method
[25]	Radiant floor	Rule-based control	Supply water temperature	Floor surface temperature	2°C	Experiments, simulation
[46]	Radiant floor	Rule-based control	Supply water flow rate	Floor surface temperature	2°C	Experiments
[63]	Radiant ceiling	Rule-based control	Supply water temperature	Supply water temperature	1°C	Simulation
[64]	Embed system, radiant ceiling, heavy radiant floor	Rule-based control	Supply water flow rate (temperature fixed at 14°C)	Surface temperature	1°C	Simulation
[65]	capillary-mat radiant ceiling	MPC	Supply water temperature	Supply water temperature (at least 16°C)	Not mentioned	Simulation
[52]	Radiant cooling panel	Multi-objective control based on reinforced learning	Supply water temperature	Supply water temperature	0°C	Simulation
[66]	TABS	Adaptive predictive control	Supply water temperature	Supply water temperature	2°C	Simulation
[51]	TABS	MPC	Supply water flow rate (on/off)	Moisture content of slabs (predicted by MPC)	N/A	Simulation
[67]	TABS	Rule-based control	Supply water flow rate (on/off)	Surface temperature	0°C	Simulation

with surface temperatures below the air dew point temperature while minimizing concerns regarding condensation. Xing et al. [20] defined passive condensation prevention methods, where the term “passive” denotes that the dew-free operation of radiant cooling terminals can be achieved without additional control strategies or external energy consumption. These condensation-free radiant cooling terminals are capable of independently preventing condensation without the need for humidity control, thereby providing the potential to be integrated with natural ventilation to achieve higher energy efficiency for space cooling in buildings. Based on the configuration of radiant cooling terminals, they are categorized into three distinct types: membrane-based liquid desiccant radiant cooling, cover-shield-assisted radiant cooling panels, and surface coating-based radiant cooling panels. From a physical mechanism perspective, most of the passive condensation prevention effect is achieved by keeping the partial pressure of vapor in the vicinity of the cooling surface at a level significantly lower than that in the humid ambient air.

5.1. Membrane-based liquid desiccant radiant cooling terminals

Membrane-based liquid desiccant technology has been extensively investigated for air dehumidification [73]. A semi-permeable membrane separates moist air and liquid desiccants in two sides. Water vapor can pass through the membrane and be absorbed by the liquid desiccants. Notably, even when the membrane surface temperature falls below the space dew point, condensation does not occur on the surface. This dew-free operation is attributed to the significantly lower vapor partial pressure at the membrane surface compared to that in the indoor bulk air. Leveraging this characteristic, chilled liquid desiccants can be directed into a membrane-based radiant cooling terminal to achieve simultaneously dehumidification and cooling for indoor environments (Fig. 4).

The concept of membrane-based liquid desiccant radiant cooling panel was first proposed in 2010 [74], whose research demonstrated that, for an air stream with an inlet temperature of 21.6°C and relative humidity of 67% flowing over the panel surface, a humidity reduction of 2 g/kg and a temperature drop of 0.8°C could be achieved [74]. Regarding the impacts of membrane-based liquid desiccant radiant cooling panels on indoor temperature and humidity, CFD simulations [75], experiments [76] and thermodynamic modelling [77] have been employed to conduct relevant investigations. Additionally, models have been developed to study the indoor thermal environment [78] and energy performance [78,79] of the combined liquid desiccant membrane cooled ceiling and displacement ventilation system. Key findings from these studies included that the liquid desiccants-cooled ceiling can deliver a similar thermal comfort level compared with conventional system and provide a better dehumidification performance for indoor air, while the energy efficiency can be improved by utilizing solar collectors to regenerate the liquid desiccant.

5.2. Cover-shield assisted radiant cooling panels

Cover-shield assisted radiant cooling panels use an infrared(IR)-transparent layer as the outer covering of a radiant cooling panel to separate the panel’s cooling surface from humid ambient air [80]. A sealed air layer is formed between the cover and the panel surface. This air layer is maintained in a dry state by desiccant packs placed within it. As a result, the vapor partial pressure in the sealed air layer is lower than that in the ambient air. This configuration allows the panel surface temperature to be maintained at a lower level, thereby creating a larger radiant heat transfer potential between the panels and sources.

The concept of cover-shield-assisted radiant cooling panels is widely acknowledged to have been first proposed by Morse in the 1960s [81]. Teitelbaum et al. developed a prototype of this panel using plastic film as a cover [82] and subsequently conducted a full-scale field study [83]. Their findings demonstrated that in a hot ambient environment (with an air temperature of 30°C), thermal satisfaction could be achieved solely through thermal radiation between the human body and the radiant cooling panels. Additionally, the field test indicated when the air dew point temperature was approximately 23.5°C, the lowest temperature of chilled water could reach 10.3°C but with no condensation observed on either the panel surface or the film surface.

In recent years, the concept of using cover-shield to avoid condensation for radiant cooling panels (Fig. 5) has attracted substantial

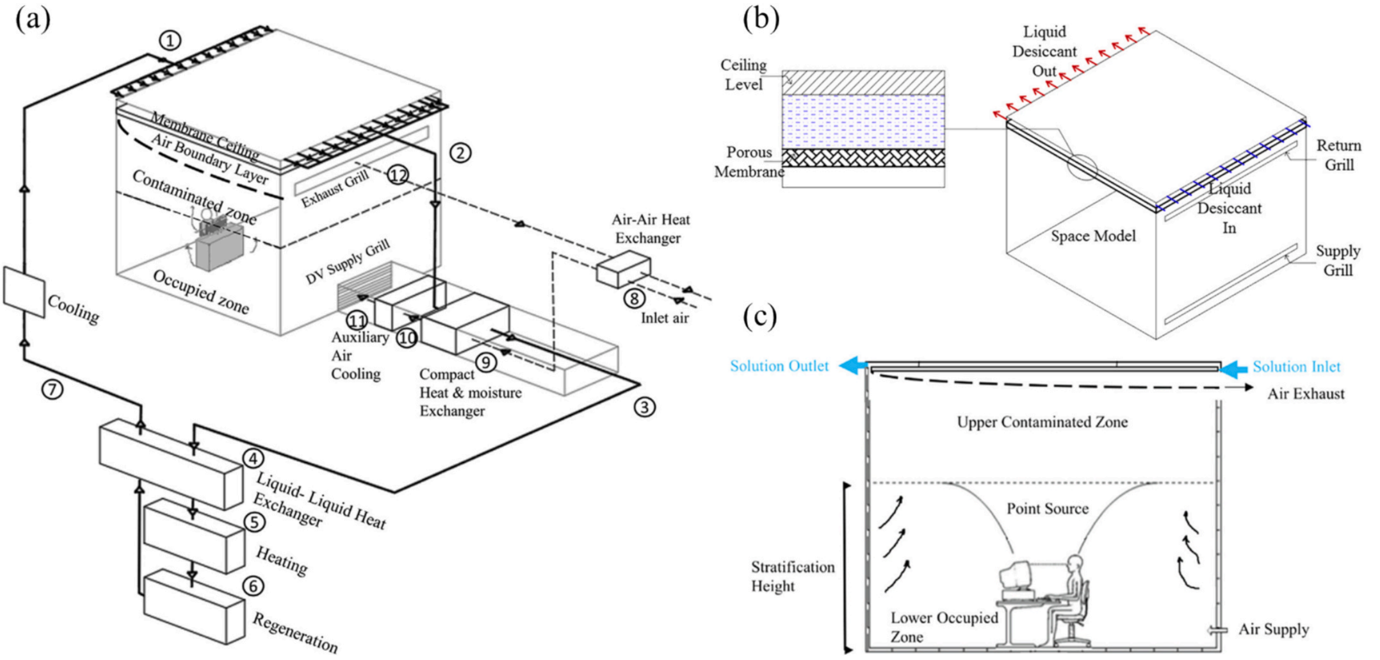

Fig. 4. Schematic of the membrane-based liquid desiccant cooling ceiling. (a) cascade system for indoor air-conditioning [76]. Copyright 2019, Elsevier. (b) The component of liquid desiccant cooling ceiling [148]. Copyright 2017, Elsevier. (c) Illustration of a room conditioned with the liquid desiccant cooling ceiling [76]. Copyright 2019, Elsevier.

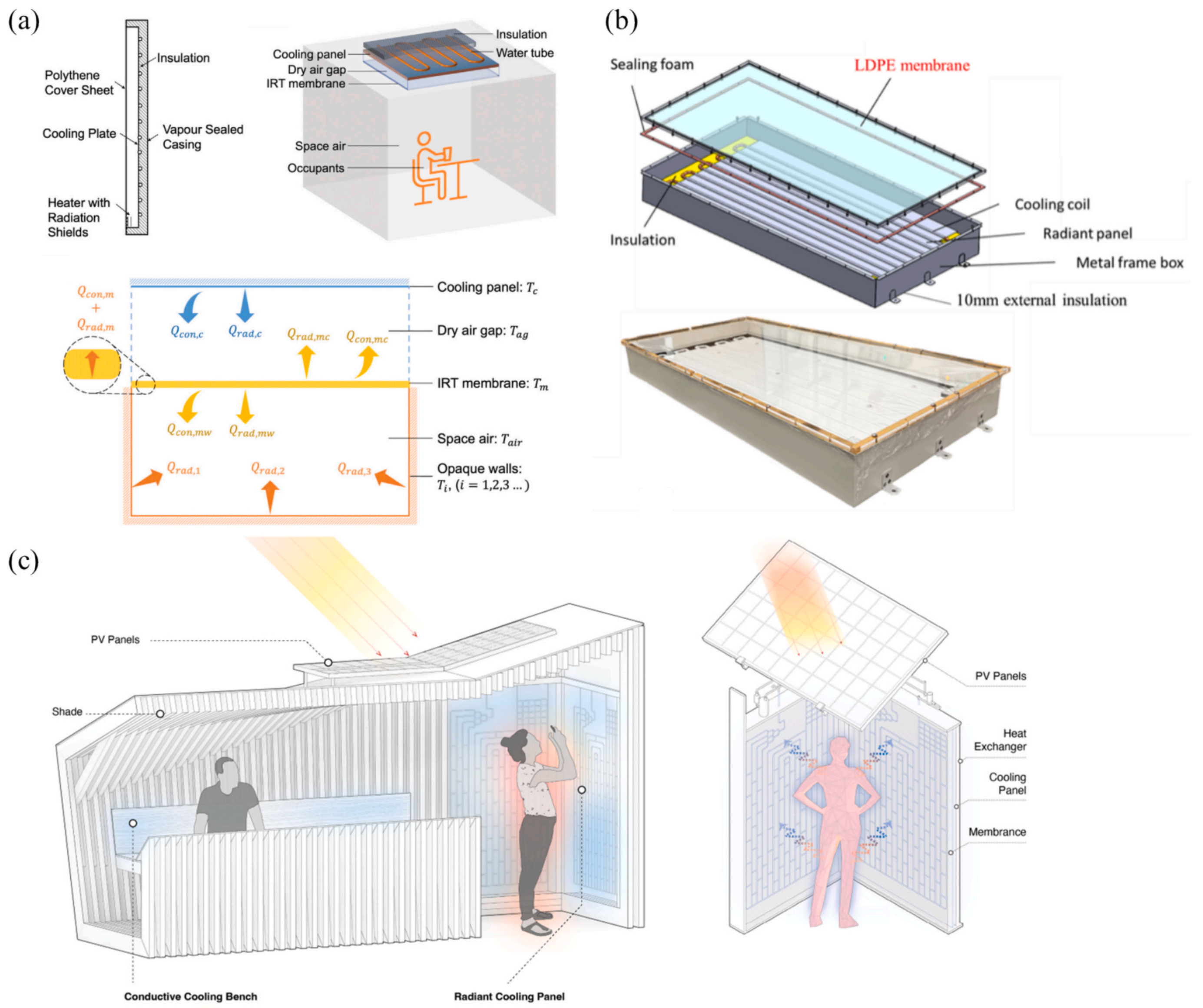

Fig. 5. Infrared transparent film-covered radiant cooling panels. (a) Schematic of heat transfer process [87]. Copyright 2023, Elsevier. (b) Configuration of a panel prototype [95]. Copyright 2024, Elsevier. (c) Application in an open-air cooling shelter [98]. Copyright 2026, Elsevier.

research attention, which has been systematically summarized in review articles [80,84]. For instance, Xing et al. [85,86] developed a theoretical heat transfer model to study the cooling capacity of film-covered radiant cooling panels. Their analysis identified key factors influencing the cooling capacity, including the air layer thickness and the cover IR transmittance, in addition to the temperature of the panel cooling surface. Zhang et al. [87,88] studied the thermal performance of film-covered radiant cooling panels in indoor environment and their impacts on thermal comfort using an experimentally validated numerical model. Their work defined the feasible range of panel surface temperature, indoor air temperature, and indoor air humidity that simultaneously avoid condensation and maintain thermal comfort. Liang et al. [89,90] developed a personalized radiant cooling strategy, which involved two membrane-assisted radiant cooling panels adjacent to occupants. This strategy was shown to provide thermal comfort in high temperature environment (air temperature: 28-30°C) when running the panel with a surface temperature of 5-10°C. Wong et al. [91] proposed a panel involving a vacuum layer sealed by IR-transparent rigid acrylic plate cover and aluminum frame, where ultra-high cooling capacity was achieved with low-temperature refrigerant as the cooling medium.

By taking advantage of the anti-condensation feature, cover-shield-assisted radiant cooling panels can be applied in naturally ventilated spaces even in hot and humid regions [92]. An energy simulation research revealed that combining natural ventilation with theses panels could achieve energy saving of 10–40% in buildings across diverse climate zones [93]. Yang et al. [94] and Liang et al. [95] explored the potential of using membrane-assisted radiant cooling panels in totally open spaces in outdoor environments. Their results showed that the mean thermal sensation vote (MTSV) of people cooled by the panels was 0.6–1.5 units lower than the non-cooled group. Notably, under asymmetric radiant cooling, a neutral state ($-0.5 < \text{MTSV} < 0.5$) of subjects was achieved even in outdoor environments with strong thermal stress. Their test on the thermal performance of the panels in hot and humid outdoor conditions indicated that vertical panels could achieve a cooling capacity of nearly 200 W/m^2. Simulation models were developed to study the thermal comfort [96] and thermal performance [97] of radiant cooling in outdoor settings. Bae et al. [98] found that an open-air cooling shelter using cover-shield-assisted radiant cooling panels could reduce people's thermal stress by 35–45%, meanwhile the cooling demand of the shelter could be totally met by solar energy. Abraham et al. [99]

developed a visibly transparent and infrared-reflective surface to further improve the energy efficiency of cover-shield-assisted radiant cooling in open spaces.

5.3. *Surface coating*

Two approaches have been developed to mitigate condensation risks for radiant cooling terminals by surface coating: one focuses on regulating condensate morphology by superhydrophobic surfaces, and the other employs surface coatings as a moisture buffer to delay condensation onset.

Superhydrophobic surfaces, which are defined as surfaces with ultra-high contact angle and low contact angle hysteresis, exhibit unique condensation patterns that micro droplets can spontaneously [100] and continuously [101] depart from the surface. The departing condensation droplets are sufficiently tiny to be imperceptible to humans, based on which superhydrophobic surface coatings were developed for metal radiant cooling panels to facilitate dew-free operation [102]. It was indicated that the maximum diameter of condensation droplets departing an aluminum-based superhydrophobic surface can be constrained less than 160 μm during eight-hour condensation with a sub-cooling degree of 7.9°C, while the maximum droplet formed on a normal aluminum plate reached almost 4 mm in comparison [103]. Theoretical analysis demonstrated that the nucleation free energy barrier and the nucleation rate of superhydrophobic surfaces are the key factors influencing the capability of inhibiting condensation [104]. By enabling radiant cooling panels to be operated at temperatures below the space dew point, the cooling capacity can be significantly enhanced by the expanded heat exchange temperature difference as well as additional condensation heat transfer between the panel surface and indoor

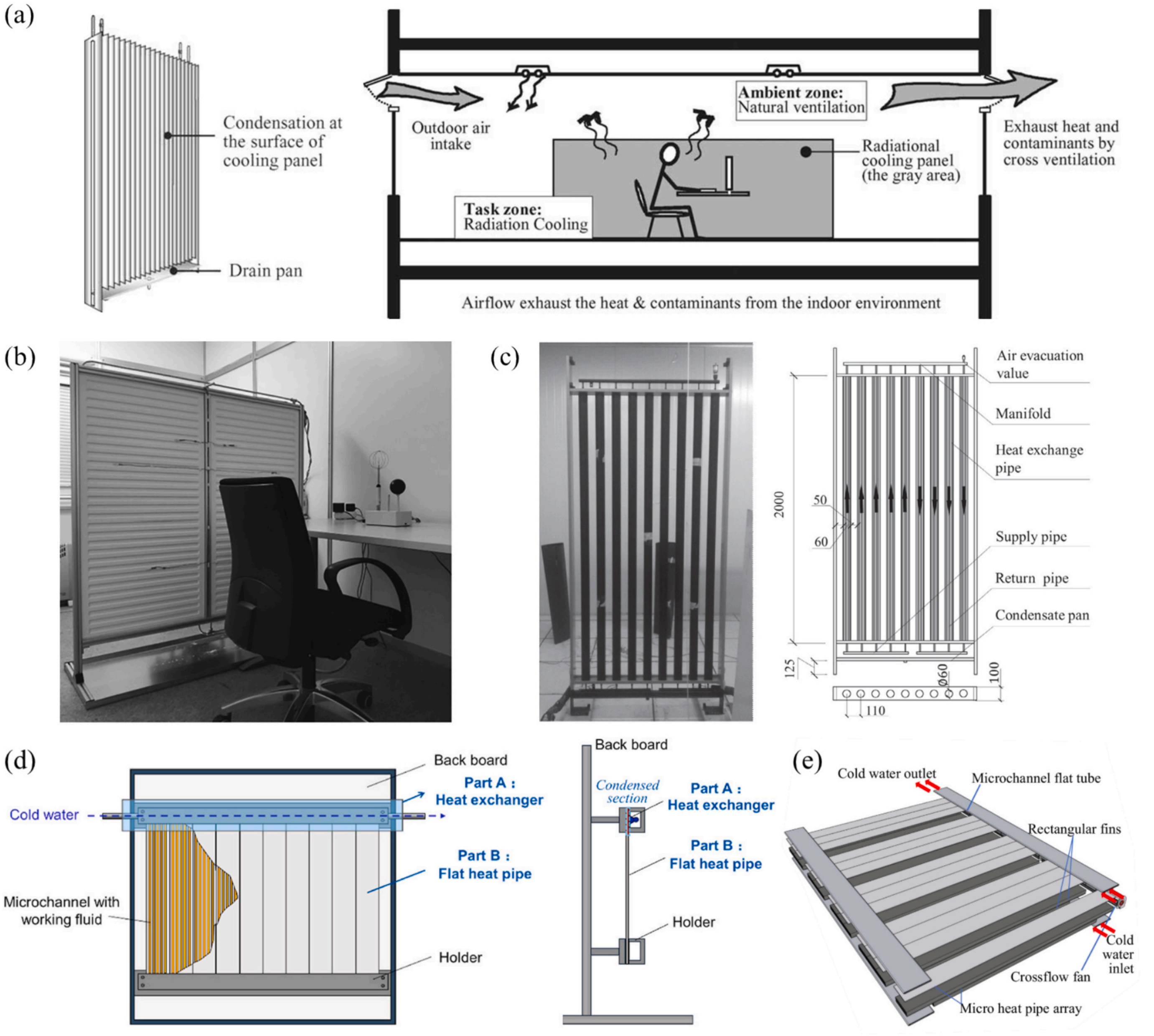

Fig. 6. (a) Schematic of condensation-managed radiant cooling panel and the concept of combining natural ventilation [110]. Copyright 2004, Elsevier. (b) The view of condensation-managed panels in office settings [112]. Copyright 2021, Elsevier. (c) The photo of a condensation-managed terminal device [119]. Copyright 2020, Elsevier. (d) The schematic of a condensation-managed radiant cooling terminal with flat heat pipe [115]. Copyright 2021, Elsevier. (e) Configuration of a condensation-managed radiant-convective terminal with micro heat pipe array [117]. Copyright 2025, Elsevier.

environment [105].

A second strategy is to use hygroscopic materials as surface coatings to act as a moisture buffer to retard condensation. For instance, Chen et al. [106,107] proposed a sepiolite composite coating for radiant cooling panels to suppress surface condensation. The coating exhibited much higher moisture adsorption capacity under high-humidity environments compared with commonly used decorative gypsum and diatomite coatings, which extended the time lag between when the panel surface cooled below the air dew point and when the first condensate appeared. The condensation retardation duration of the coating was found to be dependent on two key factors: ambient air humidity and the temperature difference between the panel surface and the air dew point. The moisture buffer coating can be regenerated by releasing absorbed vapor into ventilated air, allowing for sustained condensation-free operation in buildings [108]. Zhang et al. [109] developed two types of metal–organic framework (MOF)-based composite coatings for ceiling radiant cooling panels. Their findings demonstrated that the condensation retardation performance of these coatings is affected by their moisture adsorption capacity.

6. Condensation-managed radiant cooling panels

Radiant cooling panels may be operated with a surface temperature below the air dew point if condensate can be collected and removed without disrupting indoor environment quality. Hence, metal radiant cooling panels integrated with a drainage unit have been developed (Fig. 6). Such condensation-managed radiant cooling panels offer the potential to provide higher cooling capacity while enabling integration with natural ventilation to reduce energy consumption. Meanwhile, dehumidification of indoor air can be achieved when condensate formed on the panel surface is drained out of indoor spaces.

The performance and application of this condensation-managed radiant cooling concept have been extensively investigated in the existing literature, as summarized in Table 2. Song and Kato [110] investigated the cooling performance of a vertical radiant panel combined with natural cross ventilation in office rooms by CFD simulation. Their proposed system demonstrated the ability to use radiant cooling panels for both cooling and dehumidification of occupied space in hot and humid seasons, while simultaneously leveraging natural ventilation to provide cooling in transitional seasons. Koca and Atayilmaz [111] evaluated the cooling capacity of a wall-mounted condensing panel by experiments. Their results indicated that the condensation heat flux contributed 11–15% of the total cooling capacity when the panel was operated with a surface temperature 5°C lower than the air dew point. Teufl et al. [112] found that a thermally acceptable environment can be maintained by a vertically positioned radiant panel with slight condensation under conditions with ambient air temperature below 30°C and relative humidity below 50%. Jiang et al. [113,114] proposed a radiant cooling terminal that used refrigerant as cooling medium. Their measurement and analysis showed that latent cooling accounts for

Table 2
Comparative analysis of performance metrics for the condensation-managed radiant cooling systems across literature.

Study	Year	Method	Panel configuration	Cooling medium	Panel positioning	Cooling conditions	Cooling capacity	Ratio of latent cooling	Research focus
Song and Kato [110]	2004	Simulation	Metal panel with drain pan	Water	Vertical	Air: 29.5°C, 61%RH Panel: 18.3°C	113.7 W/m^2	8.6%	Thermal environment, energy consumption
Koca and Atayılmaz [111]	2016	Experiment	Metal panel with drain pan	Water	Vertical	Air: 22.5-23°C, 62–65%RH Panel: 10.6-14°C	66.3–102.4 W/m^2	11–15%	Cooling capacity
Zhao et al. [118]	2018	Experiment	Fin heat transfer panel with drain pan	Refrigerant	Ceiling	Air: 21.6–23.5°C, Refrigerant: 6-7°C	167.7–197.3 W/m^2	N/A	Cooling capacity, heat transfer
Shu et al. [119]	2020	Experiment	Parallel heat exchange pipes with drain pan	Water	Vertical	Air: 26°C, 60% ~ 80%RH Cold water: 7.7°C ~ 18.5°C	3.5–34.2%	3.5–34.2%	Cooling capacity, condensation heat transfer
Wang et al. [120]	2020	Experiment	Fin heat transfer panel with drain pan	Refrigerant	Ceiling	Air: 21.5–23.7°C, Refrigerant: 6-7°C	208.0–222.1 W/m^2	N/A	Cooling capacity, heat transfer
Teufl et al. [112]	2021	Experiment	Metal panel with drain pan	Water	Vertical	Air: 28-30°C, 45%RH Panel: 10-30°C	N/A	N/A	Thermal environment, thermal comfort
Jiang et al. [113,114]	2021	Experiment, numerical analysis	Steel panel with condensation collection unit	Refrigerant	Vertical	Air: 26°C, 60% RH Panel: 17.2°C (selected one)	621.5 W/m^2	17.3%	Cooling capacity, heat transfer
Wu et al. [115]	2021	Experiment	Fin heat exchanger, flat heat pipes with drainage	Water	Vertical/ inclined/ ceiling	Air: 34°C, 45% Panel: 7.0°C ~ 17.2°C	104.4–357.4 W	0–26.4%	Cooling capacity, condensation heat transfer
Tang et al. [121]	2021	Simulation	Metal panel	Water	Ceiling	Air: 28°C, 70% Water: 18°C	38.7 W/m^2	N/A	Anti-condensation operation
Zhao et al. [116]	2022	Experiment	Fin heat exchanger, flat heat pipes with drainage	Refrigerant	Vertical	Air: 26C, 63% Refrigerant: −7.0°C	1160–2604 W	3.9–15.9%	Cooling capacity, dehumidification, thermal environment
Aoyama et al. [122]	2023	Experiment, simulation	Radiant panel	Refrigerant	Vertical	Panel: 9.5–16.6°C	252–360 W	N/A	Thermal comfort, cooling capacity
He et al. [117]	2025	Experiment	Microchannel flat tube, micro heat pipe array,	Water	Vertical	Air: 28°C, 71% Water: 8-16°C	322.0–617.1 W/m^2	25%	Dehumidification, cooling capacity

17.3% of total cooling capacity. Separately, mixed radiant-convective cooling terminals with drainage units have been developed to achieve high cooling capacity while enhancing indoor dehumidification [115–117]. These terminals incorporate an air–liquid heat exchanger, a flat heat tube (serving as radiant cooling surface), and a cross-flow fan to enhance convective heat transfer. By regulating the temperature of the cooling medium, nearly 25–26% of the total cooling capacity could be allocated to remove latent load for indoor environments.

Typically, these radiant cooling panels are installed in a vertical or inclined position to facilitate condensate drainage. For ceiling-mounted panels, a fin heat transfer panel has been proposed to utilize the low-temperature refrigerant to achieve high cooling capacity for indoor spaces. A draining pan was placed beneath the panel, and the refrigerant temperature was controlled to ensure the pan bottom surface temperature was higher than the space dew point to avoid surface condensation [118,120]. Another strategy is employing an intermittent supply of chilled water to inhibit the formation of large condensation drops. By taking advantage of the slow process of condensation [123] and the evaporation of condensate [124] during the off-period of chilled water supply, a pulse width modulation (PWM) control for condensation dripping prevention of radiant cooling panels has been proposed [121]. The control method involved a fixed 20-minute on-period duration with low-temperature chilled water supply and an adjustable off-period duration without chilled water supply to allow condensate evaporation. The findings indicated that, under the studied indoor condition with air temperature of 28°C and relative humidity of 70%, setting the off period to 48 min could eliminate residual condensate on the panel via evaporation, thus eliminating the risks of droplet dripping throughout the control cycle. It was also found that the cooling capacity of panels operating with PWM control was 10% higher than that of panels using a conventional control strategy, where the supplied water temperature was maintained at 0.5°C above the dew point.

Overall, the advantages of condensation-managed radiant cooling terminals include providing latent cooling [117], enabling user-centric cooling by deployment around occupants [112], facilitating energy savings through integration with natural ventilation due to condensation manageability [110], and enhancing total cooling capacity through combining convective component [115]. Furthermore, condensation-managed terminals can be designed and manufactured based on common metal radiant cooling panels, allowing for low-cost and fast deployment in buildings. Since vertically arranged panels are conducive to condensate water drainage, such configuration exhibits superior performance compared with horizontal layout. Regardless of the installation location of the terminals, drainage must be carefully managed to avoid adverse impacts of liquid water on building materials and indoor air quality.

7. Condensation prevention in engineering applications

7.1. Condensation prevention considerations in standards and design guidelines

The methods of condensation prevention have been widely discussed in standards and guidelines, as summarized in Table 3. Condensation prevention starts with a proper design of radiant cooling systems. Take radiant cooling panel system design as an example, the first and basic step is to determine the design indoor climatic condition which includes the design indoor air dew point temperature. Then the sensible and latent load can be calculated by introducing outdoor climatic data, the supply rate of fresh air, the number of occupants, and other sensible and latent heat sources. The cooling load is handled by the combination of the radiant cooling system and the ventilation system. All the latent load and part of the sensible load are handled by the supply air which should be cooled and dehumidified. The other part of the sensible load will be handled by radiant cooling system. The lowest surface temperature of the radiant system is determined by the limit of not leading to surface

Table 3
Condensation prevention considerations in standards and guidelines.

Document	Region	System	Condensation prevention considerations
ASHRAE Handbook [125]	U.S.	Panels Embed system TABS	• Air-handling system must provide ventilation and handle latent loads for a stand-alone radiant cooling system. • Avoid placing cooling panels in or adjacent to high-humidity areas like a lobby entrance or a kitchen. • Panel water temperature controlled at least 0.5℃ above the indoor design dew-point temperature. • When the panel chilled-water system is started, the circulating water temperature should be maintained at indoor air temperature until the indoor relative humidity is at design value. • The cooling water leaving the cooling dehumidifier can be used for the panel water circuit if the dew point of air leaving the dehumidifier approaches the leaving water temperature. • Hygroscopic chemical dew-point controllers are required at the central apparatus and at various zones to monitor dehumidification if chemical dehumidification is used. • Air supply rate should be near maximum volume to ensure adequate dehumidification before the cooling ceiling panels are activated when variable-air-volume system is used.
REHVA Design Guidebook No. 07 [5]	Europe	Panels Embed system insulated from main building structures TABS	• Indoor surface condensation is prevented by limiting the supply water temperature according to the dew point temperature in the space. • Dehumidification ventilation help achieve lower dew point and therefore increase cooling capacity. • The temperature of cooling radiant surface should not exceed the comfort limits (17℃ for wall and ceiling cooling, 19℃ for floor cooling). • For floor cooling, the supply water temperature must be controlled with 1℃ higher than dew point. A humidity sensor should be installed in the building or space and connected to central control unit.
EN 1264 [126]	Europe	Surface embedded system	• For cooling systems the dew point limits the temperature of the cooling water on the regional value or other design values. • In practice, the inlet temperature of the cooling water, that is the lowest system temperature, has to be

(*continued on next page*)

Table 3 (*continued*)

Document	Region	System	Condensation prevention considerations
			limited up to 1 K below the design dew point.
EN 15377 [127]	Europe	Embed system	• For surface cooling systems, a control device shall be installed to prevent condensation on the cooled room surfaces and/or supply water pipe. • Minimum surface temperatures ($\theta_{S,\min}$) are recommended based on considerations on comfort and condensation. For floor cooling, $\theta_{S,\min} = 19^{\circ}\mathrm{C}$. For wall cooling, $\theta_{S,\min}$ is designed by considering dew point and down draught of cold air. For ceiling cooling, $\theta_{S,\min}$ is mainly limited by the dew point.
ISO 11855 [128]		Embed system	• For cooling it is also recommended to control the supply water temperature based on the zone with the highest dew point temperature. • The control of water temperature should be influenced by the room temperature and humidity of representative space. • Both condensation on internal cooled surfaces or condensation in critical parts of the building should be avoided, which can be done by a central control of the supply water temperature and limit on the minimum water temperature based on a measured dew point in the conditioned space. • For floor cooling, it is recommended to select a minimal supply water temperature equal to the supposed maximal dew point temperature to avoid condensation on the floor surface and to guarantee the selected cooling capacity of the radiant system. • An accurate prediction of the maximal suggested dew point in the space by considering the outdoor air conditions and indoor latent loads is necessary for combined floor cooling and natural ventilation.
ISO 18566 [129]		Radiant cooling panel system	• The panel water supply temperature should be maintained at least 1 K above the room design dew point. • The frequently applied dehumidification method is using cooling coils, and the cooling water leaving the cooling coil can then be used for panel water circuit. • When chemical dehumidification is used, hygroscopic chemical-type dew point controllers are required at the central apparatus and at various zones to monitor dehumidification. • When a variable air volume is used, the air supply rate should be near the maximum volume to assure adequate dehumidification before the cooling ceiling panels are activated. • Design dew point temperature is the basis on the determination of design and operation strategies during cooling period. The minimum permissible effective cooling panel surface temperature is determined by that will not lead to surface condensation and thermal discomfort at design condition. • The precooling and dehumidificaton of outdoor fresh air is necessary, and can be carried out with the combination of general air handling unit such as dedicated outdoor air system and energy recovery wheel.
JGJ142 [130]	China	Embed system	• The temperature of radiant cooling surfaces should be 1-2℃ higher than indoor dew point temperature. • Radiant cooling system should be combined with dehumidification system or fresh air system. • Condensation control should be implemented in most humid rooms/zones. • The indoor dew point temperature should be detected by dew point sensor or calculated by humidity transmitter. • Dew point sensor should be installed on the surface of chilled water pipes or radiant cooling surfaces.

condensation and thermal discomfort. Finally, the area of radiant surface, the flow rate of panel cooling water as well as the water temperature rise are determined.

These standards and guidelines share the same principle for condensation prevention that dew-point temperature serves as the reference for defining minimum allowable surface or chilled water temperatures. To achieve this point, the monitoring of space dew-point and surface or chilled water temperature must be implemented for system control. Chilled water temperature is generally recommended to implement condensation prevention since it is easier to measure than surface temperature. The mandatory safety margin above dew point enforced to avoid condensation may differ. For instance, ASHRAE Handbook [125] recommended 0.5℃ offset between panel water temperature and indoor dew-point, while Chinese standard JGJ142 [130] requires 1-2℃ margin between surface temperature and space dew-point. To prevent condensation at the start-up stage of radiant cooling system, ASHRAE Handbook [125] suggests keeping the chilled water temperature at the level of indoor temperature first and provide maximum ventilation rate to achieve fast dehumidification.

7.2. Condensation prevention strategies adopted in engineering cases

Currently, radiant cooling systems have been successfully applied in various types of buildings like residential buildings [131], office [132], educational buildings [133], and large-space buildings [134]. The early applications were mainly located in Europe [5] and North America [135] where climate is temperate without too much condensation concern when the buildings were constructed. In recent decades, more practices have been successfully implemented in hot and humid areas. Since the primary investment of a radiant cooling system is typically higher than all-air conditioning system, buildings with radiant cooling systems often begin with ambitious energy efficiency target to save operation cost, which enables these buildings to have more refined design and high-quality construction.

The strategies adopted for condensation prevention in the selected engineering cases reported in academic publications are summarized in Table 4, where the climate is characterized based on the Koppen climate classification. It can be seen that more cases are reported in hot and humid areas since condensation prevention is crucial for the success of radiant cooling systems in such areas. Furthermore, compared with

Table 4
Condensation prevention strategies adopted in engineering cases.

Reference	Location	Climate	Building type	Radiant cooling System	Air handler	Condensation prevention strategies
[40]	Hamburg, Germany	Cfb	Factory	Radiant floor	AHU	Outdoor air was supplied with humidity ratio of 8–9 g/kg after dried in a lithium chloride desiccant wheel. The radiant floor had a cooling water supply of 18℃ that is cooled through borehole heat exchanger.
[136]	Hong Kong, China	Cwa	Office	Ceiling radiant panel	PAU	Ceiling surface temperature was maintained at 2℃ above dew point temperature (at least 16℃). Indoor humidity was controlled at 55% RH or below with supply fresh air dew point at 11°C dehumidified by dual coil.
[137]	Tokyo, Japan	Cfa	Office	Ceiling radiant panel	AHU/ DOAS	Supply air handled by desiccant-based dehumidification in AHU. Outdoor air handled in DOAS.The dehumidified air is supplied above the ceiling radiant panels and returned at the floor level.
[138]	Tokyo, Japan	Cfa	Office	TABS	DOAS/ AHU	A desiccant DOAS is used to control humidity. The air-cooled chillers supply chilled water at two different temperatures: 7℃ for the air conditioning and 12℃ for TABS. The chilled water for TABS is supplied at 16℃ after undergoing heat exchange.
[42]	Beijing, China	Dwa	Office	TABS	PAU	Supply water temperature 9-11℃ for both radiant cooling system and PAU. Slab surface temperature was approximately 21℃ and was higher than the indoor air dew point.
[139]	Hyderabad, India	Aw	Office	TABS	DOAS	Direct expansion coil in DOAS for achieving dehumidification, but it is less efficient compared to chilled water coil.The space dew point kept below the chilled water supply temperature.
[140]	Shenzhen, China	Cwa	Office	Radiant panel	PAU	Fresh air dehudmidified by fresh air unit with liquid desiccant and supplied with temperature of 17.1℃ and humidity ration of 6.2 g/kg. Chilled water with temperature of 17.5℃ supplied to radiant panels.
[141]	Guangzhou, China	Cwa	Office	Ceiling radiant panel	PAU	Fresh air cooled and dehumidified in PAU with 7℃ chilled water supply. After cooling fresh air, the chilled water was supplied to a plate heat exchanger to generate chilled water of 16℃ to cool the radiant panels.
[41]	Berkeley, U.S.	Csb	Office	Radiant slab	DOAS	The only cooling source for radiant slab and DOAS is a cooling tower. The supply water temperature for radiant cooling is limited not below to outdoor wet-bulb temperature.
[142]	Xi'an, China	Cwa/ Dwa	Airport	Radiant floor	PAU	Outdoor air is dehumidified by PAU with liquid desiccant and supplied to area near floor through displacement ventilation Dry FCUs with condensing plates are placed near the doors and windows instead of radiant floors to avoid condensation in perimeter zones. The supply water temperature for radiant floor is 16℃. The marble type floor surface temperature is approximately 22–23℃, while the space dew point is near 16–17℃
[143]	Singapore	Af	Office	Radiant panels	DOAS	Radiant panel surface temperature controlled between 16℃ and 21℃. Outdoor hot and humid air cooled and dehumidified in DOAS, and supplied with a state of 20℃ and 45%RH. Indoor air conditions maintained at 26℃ and 50%RH
[144]	Sacramento, U. S.	Csa	Retail	Radiant slab	DOAS	Chilled water with 14.4℃ supply and 17.2℃ return maintained a floor surface temperature of 18.9℃. The space dew point was controlled not lower than 14.4℃ by a DOAS to prevent frost in spaces with refrigerated cases.
[145]	Putrajaya, Malaysia	Af	Office	Radiant slab	PAU	The ceiling surface temperature was maintained at 2°C or higher than the dew point temperature of the circulated indoor air. Indoor air humidity maintained in the range of 50–60% by modulating the intake of conditioned fresh air to save the risk of condensation.
[146]	Bankok, Thailand	Aw	Airport	Radiant floor	AHU	The water supply temperature of radiant floor was limited to 13℃ to reduce condensation risk; The floor surface temperature was controlled above 21℃. The indoor climate conditions were designed with room temperature of 24℃ and relative humidity of 50–60%. Extra cooling capacity was used as a safety measure when the humidity levels were too high
[147]	Bregenz, Austria	Cfb	Museum	TABS	PAU	The water was supplied to pipes with a temperature of 22°C both for heating in winter and cooling in summer. The room air temperature and humidity in summer is maintained at 22–26°C and 52%–58% respectively. Outdoor air with constant temperature and humidity was supplied with a volume flow of 750 m^3/h through slots of displacement ventilation.

residential buildings, public buildings like office buildings and transportation center usually have dedicated dehumidification and ventilation systems to prevent condensation. Hence, most cases are observed in these types of buildings.

Typically, air handling units are combined with radiant cooling system to dehumidify outdoor air and handle indoor latent loads, as well as provide fresh air to meet requirements of indoor air quality. The principle of condensation prevention in these engineering cases is that temperature of radiant cooling surfaces must be kept higher than the space air dew point. This is achieved by carefully controlling the indoor humidity and chilled water temperature of hydronic systems. The indoor humidity is maintained at desired level by ventilating the dehumidified air into buildings. The moisture is removed either by cooling dehumidification [139] or desiccant dehumidification [137]. These two dehumidification strategies were both applied in various buildings types (like office buildings or airport) and combined with different radiant cooling systems (including TABS, radiant floor, and radiant cooling panel).

When cooling dehumidification is applied, the temperature of chilled water supplied to radiant cooling system is always higher than that supplied to air handling unit in most cases. This is achieved by using separate cooling sources [139] or cascade utilization of chilled water [141]. The cooling dehumidification strategies were adopted in various climate zones like tropical wet climate [145], humid subtropical climate [136], and Mediterranean climate [144]. To enhance the dehumidification performance in compact primary air unit, a dual-coil system was applied in a case in hot and humid Hong Kong [136]. Regarding desiccant dehumidification, both liquid desiccant [140,142] and solid desiccant system [40] were reported in engineering practices. The desiccant dehumidification strategies were mainly adopted in humid areas including humid-temperate climate [40] and humid-subtropical climate [138,140]. In moderate climate conditions, outdoor air can be directly supplied to remove indoor latent load while natural cooling sources can be employed to handle sensible load through radiant cooling systems [41,147].

Despite temperature and humidity control, strategies of using convective cooling terminals in perimeter zones near doors, windows, and facades were adopted in some cases (Fig. 7), because condensation more likely occurs in those areas due to air infiltration. Besides, the convective terminals are capable of handling high cooling loads caused by solar radiation or occupants' activities, thus enhancing thermal comfort in the perimeter zone.

Condensation would not be a problem if a building is properly designed and well operated. However, condensation prevention strategies may fail due to device faults, inappropriate operation of system, unpredictable occupant behaviors, or extreme climate conditions. There are several lessons that can be learnt from the operation of radiant cooling systems in real buildings. One is that the direct expansion coil in the AHU failed to dehumidify air as precisely as expected due to the re-evaporation of condensate during the off-period of compressor [139]. Another is that the temperature of chilled water supplied to slab was set to 8℃ by an inexperienced operator to attempt to eliminate overheating complaints, and condensation occurred on slabs consequently [149]. The radiant surface temperature sometimes may be a bit lower than the space dew point at certain period in all-day operation especially when low-temperature chilled water is supplied to radiant cooling systems [42]. The occupants behavior, such as opening windows, would lead to a sudden rise of indoor humidity, which would cause mild condensation on radiant surfaces [123].

8. Discussion

8.1. *Revisiting condensation risk*

The condensation prevention strategies are usually designed to strictly avoid condensation in buildings anywhere and anytime during system operation. On the other hand, a short period of condensation on a radiant cooling surface would not cause too much trouble for occupants, as pointed out by Mumma [123]. That is because condensate formation is relatively a slow process, while facility management team can handle the condensation problem either by adjusting the chilled water temperature or shutting down the chilled water supply before condensate drips. By integrating drain units with vertical radiant cooling panels, liquid water spreading is avoided while simultaneous cooling and dehumidification can be achieved.

Enhanced tolerance of condensation may help mitigate concerns of condensation risks when applying radiant cooling systems. This is not only useful for the design, but also important in operation as unpredictable human behavior and potential climate change would causing a humidity level far more beyond the design condition. The key is knowing the dynamics of condensation on different radiant cooling surfaces as well as the impact of condensate on indoor environment quality and health of building materials. This is crucial for the evaluation of deciding how much lower the radiant surface temperature can be controlled below air dew point or how long the condensation on the radiant cooling surface can be allowed.

8.2. *Challenges and opportunities of novel radiant cooling terminals*

Advances of material science generate innovations for radiant cooling panels to achieve condensation prevention. Current research explored the anti-condensation performance and potential applications

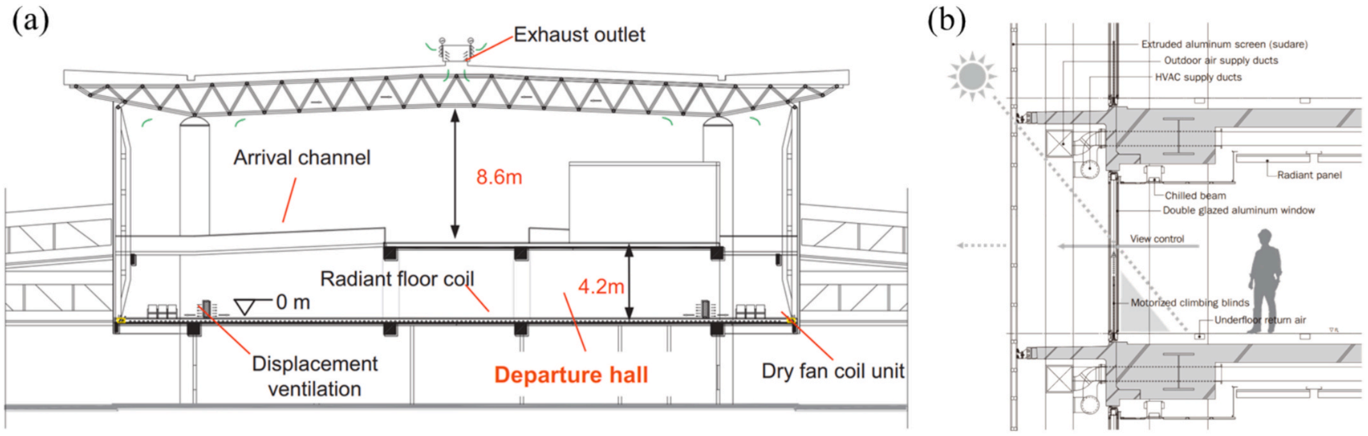

Fig. 7. Enhancing cooling capacity and prevent condensation in perimeter zones by convective cooling terminals in (a) airport [142]. Copyright 2013, Elsevier. (b) Office buildings [137]. Copyright 2016, The Hong Kong Green Building Council.

of such terminals in buildings by experiments and simulation, but there are still challenges hindering the application of these novel radiant cooling terminals in practice. As for cover-shield radiant cooling panels, though the plastic films widely used in existing research has the advantage of low cost, large-scale production, and high infrared transparency, the durability and mechanical strength of cover materials stills needs to be improved to avoid frequent maintenance [80]. Another issue less discussed in previous studies is the long-term moisture management of the air layer. For superhydrophobic coatings, challenges include the development of low-cost and large-scale superhydrophobic materials with good durability and uniformity, while the condensation performance, dripping risk evaluation, as well impacts on indoor air quality at the building scale also need a further investigation. In addition, surface dust accumulation and coating aging will degrade the performance of superhydrophobic surfaces, causing the appearance of large droplets on the surface and the increase of dripping risks. Therefore, further investigation is also required on long-term operation and corresponding maintenance strategies for superhydrophobic surface-coated radiant cooling panels. For hygroscopic coatings, the challenges include the potential mold and fungi growth inside the hygroscopic materials when the relative humidity of the materials becomes near saturation. The characteristics of condensation retardation makes the hygroscopic coatings highly suitable for addressing condensation induced by sudden humidity elevation.

Overall, the novel anti-condensation radiant cooling terminals primarily face challenges of long-term operation stability and material cost viability, which may be addressed through innovations in mechanical design, materials, and manufacturing. Nevertheless, these terminals still exhibit competitive potential by taking advantage of independently mitigating condensation risks in humid conditions, thereby reducing additional investment in condensation control components like dew-point sensors and enabling energy-saving strategies like natural ventilation. Furthermore, system design methodologies should be updated based on the characteristics of the novel radiant cooling terminals to facilitate deployment in real projects, which requires further investigation on the overall performance of energy and thermal environment of radiant cooling systems combined with these novel terminals in building-scale.

9. Conclusion

This article provides a comprehensive review on the research advancements and engineering practices of condensation prevention strategies in radiant cooling systems. These strategies are summarized and discussed in terms of humidity control, hydronic system control, and innovative anti-condensation radiant cooling terminals.

Humidity control is a critical prerequisite for the condensation prevention, which can be realized by combining cooling dehumidification or desiccant dehumidification with ventilation system. Additionally, outdoor air cooling can be applied to remove indoor latent load in temperate climates. The humidity distribution which is influenced by air flow patterns and the condition of moisture sources, should be taken into account to prevent condensation. Pre-dehumidification of indoor air is essential to avoid condensation at the start-up stage of radiant cooling systems. The duration of pre-dehumidification cannot be uniformly set due to variations in humidity dynamics caused by infiltration rate and ventilation type. Instead, the humidity level must be monitored and make sure the radiant cooling system is not operated before the humidity reaching the desired level.

To avoid condensation, the temperature of radiant cooling surface must be strictly controlled above the space dew point. The surface temperature control is achieved by adjusting the temperature or flow rate of chilled water. Typically, chilled water temperature control is rather recommended for condensation prevention. A mandatory safety margin of 0.5–2℃ above the space dew point is suggested by design guidelines for chilled water temperature control to avoid condensation. Improving the uniformity of the radiant surface temperature helps prevent condensation at the location with lowest temperature. Meanwhile, enhancing convection cooling can effectively mitigate the limitation of cooling capacity caused by condensation prevention requirements, which is achievable by optimizing the configuration of radiant cooling panels or introducing forced convection to radiant cooling surfaces.

The anti-condensation innovations of radiant cooling, including membrane-based liquid desiccant cooling ceiling, infrared transparent cover-shield radiant cooling panels, and anti-condensation surface coatings by superhydrophobic materials or hygroscopic materials, enable radiant cooling terminals to operate without relying on external humidity control in humid conditions while reducing condensation risks. However, their stability and cost viability need further improvement for long-term operation and large-scale deployment in real buildings. The condensation-managed radiant cooling panels enabling surface condensation offer high cooling capacity and dehumidification for indoor environments.

This review comprehensively and systematically summarizes the condensation prevention strategies in radiant cooling systems from the perspective of building environment, focusing on terminals, equipment, and system. Therefore, the interpretation of physics and mechanisms involved in the condensation process is slightly insufficient. In addition, the certain topics like the impact of different ventilation types combined with radiant cooling on humidity distribution is less discussed due to the lack of targeted literatures. Such limitations impede a deeper understanding of the condensation issues in radiant cooling systems. In future, attention can be put into the research associated with the condensation mechanisms of different radiant cooling surfaces, as well as the impact of surface condensation on indoor environment quality. Consequently, optimal control methods to achieve higher cooling capacity, better energy performance as well as healthy indoor environments for radiant cooling systems in humid climates can be developed. Additionally, the resilience of current condensation prevention strategies under climate change can be further investigated. As for the innovation of condensation-free radiant cooling terminals, efforts can be devoted to solving the challenges inhibiting their practical applications.

CRediT authorship contribution statement

Ziwen Zhong: Conceptualization, Writing – original draft, Investigation. **Kumar Dharmasastha:** Writing – review & editing. **Jing Du:** Writing – review & editing. **Yongxin Xie:** Writing – review & editing, Funding acquisition. **Jianlei Niu:** Writing – review & editing, Funding acquisition, Supervision.

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.

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Data availability

No data was used for the research described in the article.

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