Chapter 10
Introduction and Literature Review of the Application of Hydronic-Based Radiant Cooling Systems in Sustainable Buildings

Deok-Oh Woo and Lars Junghans

Abstract Hydronic-based radiant cooling systems have been widely utilized for their energy efficiency and offering more thermal comfort for occupants when compared to conventional convection-based cooling systems. However, the potential risk of developing condensation on the surface keeps thermo-active building systems (TABS) from being applied in buildings located in warm and humid climate regions. This chapter presents a model predictive control (MPC)-based condensation prevention approach that allows the prevention of surface condensation during the cooling periods when the TABS is in operation. Based on future conditions predicted by the dynamic models, the MPC-based condensation prevention framework adjusts the surface temperature for the TABS in ways that guarantee occupant thermal comfort and energy efficiency without the development of surface condensation.

10.1 Introduction

To accomplish the energy-efficient heating or cooling technologies in buildings, occupants' comfort should not be compromised with minimum energy input to the systems. Based on the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) Standard 55 [1], thermal comfort for a person is defined as *a condition of mind that expresses satisfaction with the thermal*

D.-O. Woo (✉)
College of Engineering, Lawrence Technological University, Southfield, MI, USA
e-mail: dwoo@ltu.edu

L. Junghans
Taubman College of Architecture and Urban Planning, University of Michigan, Ann Arbor, MI, USA
e-mail: junghans@umich.edu

M. Nazari-Heris (ed.), *Natural Energy, Lighting, and Ventilation in Sustainable Buildings*, Indoor Environment and Sustainable Building,
https://doi.org/10.1007/978-3-031-41148-9_10

environment. Generally, there are six comfort parameters that are widely accepted for determining the indoor thermal comfort for occupants: (1) air temperature, (2) mean radiant temperature, (3) air velocity, (4) vapor pressure in ambient air, (5) activity level, and (6) thermal resistance of clothing.

Among these parameters, air temperature, mean radiant temperature, air velocity, and partial vapor pressure in ambient air can be relatively easily controlled with heating or cooling technologies. However, in many cases, heating or cooling technologies are operated based on ambient air conditions only, disregarding the impacts of indoor surface radiant temperature [2]. When we disregard the impact of indoor surface radiant temperature on thermal comfort, occupants may experience discomfort conditions like radiant asymmetry [3]. People are likely to be more sensitive to asymmetry caused by an overhead warm surface than a cold surface. This leads to facts that: (1) both air temperature and indoor surface radiant temperature should be considered altogether to provide better occupants' thermal comfort, and (2) there is energy savings potential of utilizing surface radiant cooling systems on the ceiling side.

Over the past few decades, a number of cooling technologies have been examined to save buildings' cooling energy. One of the most promising strategies is to flow cold water directly through the construction layer and use these cold surfaces as a radiant cooling device to reduce the cooling load for multi-story buildings [4]. The radiant cooling system refers to using cooled shells or construction layers to remove sensible indoor heat by thermal radiation. The radiant cooling systems can be classified into non-hydronic-based systems (or air-based systems) and hydronic-based systems based on what medium they utilize. Among these two systems, the hydronic-based radiant cooling system is considered more energy-efficient because of its less transport energy input than the non-hydronic-based system. This is because, given the same volume, water has much more thermal capacity to deliver heat energy than air, leading to significant transport energy savings for hydronic-based systems than air-based systems [5].

Figure 10.1 shows a schematic comparison between forced air-based cooling systems and hydronic-based radiant cooling systems. Hydronic-based radiant cooling systems have the following advantages compared to conventional forced air-based cooling systems. First, the relatively high heat capacity of water brings the hydronic-based radiant cooling system to have a smaller distribution system size, such as piping. In general, 10-mm radius water pipes are installed within or adjacent to the radiant cooling systems at intervals of 150–200 mm [6]. On the contrary, the forced air-based systems take a larger volume of system ductwork in order to deliver the same amount of thermal energy. This small space required for a hydronic-based radiant cooling distribution system can bring greater flexibility in the architectural design practice. Therefore, many designers and planners adopted hydronic-based radiant cooling systems in many multi-story building projects to bring more freedom to the design decision process [6].

Second, the radiant cooling systems can lead to significant energy savings by isolating the control for cooling (thermal comfort control) and ventilation (indoor air quality control) [7]. In the forced air-based cooling systems, the total amount of

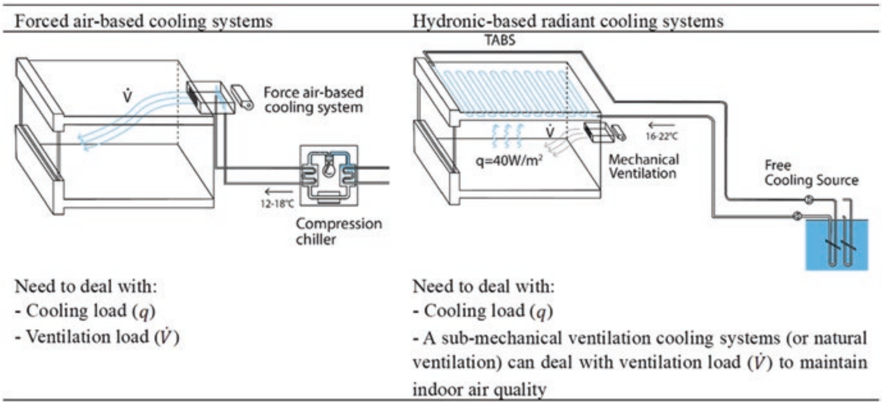


Fig. 10.1 Comparison between air-based cooling systems and hydronic-based radiant cooling systems

air conditioning is decided considering both cooling load and ventilation demand. However, the calculated supply air amount derived from the cooling demand and ventilation demand is rarely equal [6]; this discrepancy can lead to a redundant energy input for air conditioning and fan energy of the forced air-based cooling systems. Potentially, it is true that some amount of power for air conditioning can be reduced by recirculating the conditioned air within the air-based cooling systems. Still, this air recirculation strategy is not applicable for multi-story buildings with a large occupant density because most of the returned air needs to be replaced or mixed with the outdoor air to keep an acceptable indoor air quality [5].

In contrast, the radiant cooling systems allow a precise control for both cooling and ventilation by separating each other. In general, the radiant cooling systems are coupled with a sub-mechanical ventilation cooling system, such as dedicated outdoor air system (DOAS) [6]; the most of sensible cooling load is dealt with the radiant cooling systems while the rest of the cooling load and ventilation load is controlled by the sub-mechanical ventilation cooling systems. This separation in cooling and ventilation functions within the system will allow more accurate control for cooling demand and ventilation demand, thus enabling overall energy savings [5].

Third, when these radiant cooling systems are combined with the sub-mechanical ventilation cooling systems, a higher level of thermal comfort can be provided to the occupants. As mentioned above, six parameters impact human thermal comfort [8]: (1) air temperature, (2) mean radiant temperature, (3) air velocity, (4) vapor pressure in ambient air, (5) activity level, and (6) thermal resistance of clothing. Besides two personal factors (activity level and thermal resistance of clothing), the other four elements can be controlled by the cooling system to achieve a higher thermal comfort level. Conventional forced air-based cooling systems only can deal with three of these factors, ignoring the radiant temperature. Disregarding the impact of radiant temperature on thermal comfort may result in occupants' uncomfortable conditions, such as cold draft or radiant asymmetry. For example, when lightly clothed occupants are working in front of the desk under moderate indoor airspeed (<0.2 m/s), they tend to exchange more of their sensible heat through radiation than convection [6]. Therefore, when the radiant cooling systems are coupled with the sub-mechanical ventilation cooling systems, they can deal with the sensible and latent cooling load and control the radiant surface temperature, thus creating truly comfortable indoor environments for the occupants [5].

Fourth, hydronic-based radiant cooling systems can be operated more energy-efficiently than conventional forced air-based cooling systems because of their effective ways of exchanging heat through the surface radiant cooling effect [6]. Because heat exchange through radiation is more dominant than convection under the same cooling energy input [6], a feed water temperature for radiant cooling systems can be much closer to set point or room air temperature than a supply air temperature for the forced air-based system to bring the similar cooling effect to the occupants. For example, when the major source of cooling is from the vapor compression refrigeration cycle, by having the supply water temperature (from the evaporator side) close to the temperature of the condenser side where waste heat is emitted, the coefficient of performance (COP) for the chillers or heat pumps can be increased significantly [9]. In addition to that, when this condenser side is connected to a free heat sink such as a ground source loop or a cooling tower, which can be cooled down by nighttime colder outdoor air temperature, the COP for the chillers can be increased tremendously [5].

Typically, three types of hydronic-based radiant cooling systems have been identified (Fig. 10.2): radiant cooling panels, embedded surface cooling systems, and thermo-active building systems (TABSs) or thermo-active components [10]. The radiant cooling panels are composed of suspended metal panels that produce cold surfaces to exchange indoor heat by radiation. The cold surface temperature can be generated by water pipes laid on the metal panels. The embedded surface cooling system exchanges heat through the embedded water pipes within gypsum board layers, but it is insulated from the building construction layer. The thermo-active building systems (TABSs) or thermo-active components, on the other hand, flow chilled water directly through the water pipes embedded in construction layers for providing radiant cooling effect to occupants [11].

Among these three types of hydronic-based radiant cooling systems, the TABS can only exploit the thermal storage effect significantly better over the other systems by cooling down the construction layers (e.g., concrete slab) directly. The construction layers with massive material of TABS are usually pre-cooled with nighttime cooling sources (e.g., outdoor air or groundwater sources nearby) a few hours ahead

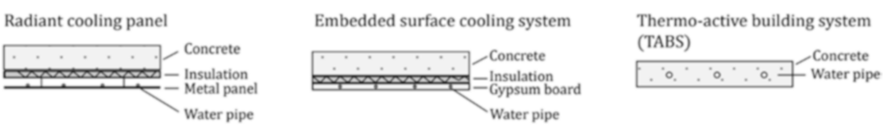


Fig. 10.2 Three types of hydronic-based radiant cooling systems

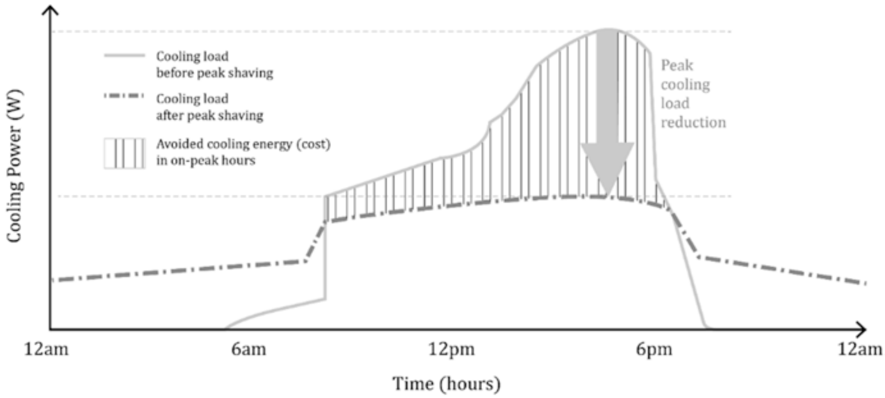


Fig. 10.3 Peak shaving with TABS

of occupancy to cope with rapidly increasing cooling load for incoming daytime hours. Later, this heat stored within the heavy construction layers of TABS during the daytime can be kept beyond the time of occupancy and is then cooled down by the nighttime free cooling sources (outdoor air or ground sources nearby) or can be cooled down during the less expensive operational cost period (Fig. 10.3). Therefore, both the peak cooling load and the operating cost for cooling can be reduced overall [12].

Besides the thermal storage effect of TABS, the low first cost for TABS is another intriguing advantage [9]. Because TABS only requires the installation of pipes or tubes inside the concrete layers, initial installation costs for new construction buildings are considered more cost-effective than the upfront cost for conventional forced air-based cooling systems (Fig. 10.4).

When utilizing the TABS in cooling mode, the following should be considered. First, the installation of TABS on the load-bearing structural systems should be avoided [7]. The TABS should be installed in less load-bearing areas because hollow pipes or tubes do not have enough load-bearing capability. Second, designers or engineers should take acoustic issues into consideration. Installing noise buffers underneath the TABS can reduce the potential noise problems that can be caused by the sound of flowing water through the embedded water pipes or tubes [5].

10.2 Thermo-Active Building Systems in Buildings

By the beginning of this century, thermo-active building systems (TABSs) are gaining more technological momentum and attention because of the significant cost-saving potential and providing high occupant thermal satisfaction level. Thus, the TABS has been widely utilized for cooling especially in multi-story buildings in central Europe (Switzerland, Germany, Austria, etc.) and started to spread out to North America and Asia partly [9].

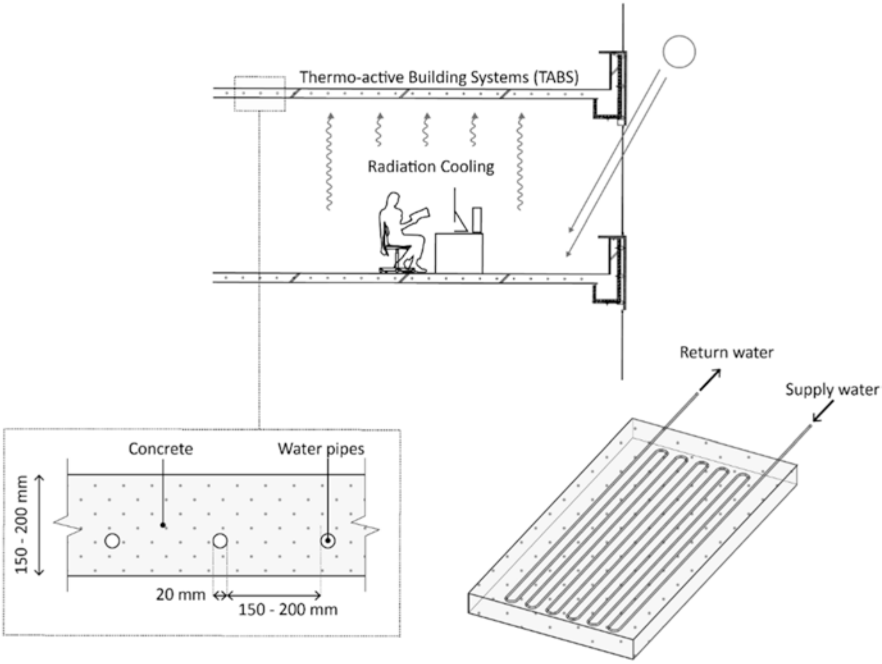


Fig. 10.4 Configuration diagram of the water pipe-embedded TABS and its operation on the ceiling

Starting from the 1990s, many practitioners and architects in Europe adopted TABS as the major cooling system for their projects. In Germany, the TABS is also one of the most widely used cooling systems for multi-story buildings. The Zollverein School of Management and Design, located in Essen, is a good precedent that resolved its design challenge by integrating TABS. The building was designed by the renowned Japanese architectural firm SANAA. This project's main challenge was to achieve the passive house standard for the building envelopes. To achieve this strict passive house standard, thick wall construction and a significant amount of insulation were required, which was quite not a favorable design condition for the team because indoor spaces would be compromised, and first cost for insulation would increase. Instead of having a massive amount of insulation materials, the engineers suggested integrating TABS with a free source of heating and cooling. For the heating purpose, the engineers designed the system to be able to pump up reused heated water from the 1000-m-deep mine shafts; in cooling mode, the cooling tower produced cold water by exchanging heat with cold nighttime outdoor air temperature. By using the free source of heating and cooling for the TABS, the thickness of building envelopes could remain at regular thickness as the designer initially wanted. Compared to the forced air-based HVAC systems, a significant amount of heating and cooling energy savings was achieved thanks to the

TABS. According to [13], the installation cost of TABS for heating and cooling systems was one-third of conventional forced air-based systems [5].

As the energy and cost savings potential of the TABS has been proven throughout many projects in central Europe, newly built building projects in North America started to adopt the TABS as a major cooling system. The Fred Kaiser building at the University of British Columbia, located in Vancouver, is a multi-story building that integrated the TABS for both heating and cooling. A cooling tower at the rooftop produces cold water from the nighttime cold outdoor temperature; the produced cold water is then distributed to each room for the purpose of cooling. The building could save more than 50% of energy compared to Canadian building code, thanks to the TABS [13].

10.3 Thermo-Active Building Systems' Challenge: Surface Condensation

As discussed earlier, thermo-active building systems (TABSs) have been successfully utilized in buildings in central Europe and partly in North America for their energy efficiency as well as providing higher levels of thermal comfort for occupants. Although the TABS has proven to be a promising cooling technology and has been widely utilized in Central Europe and partly in North America, building industries in rest regions still hesitate to accept the TABS for cooling, especially in warm and humid climatic regions [6]. This is because the radiant cooling systems, including the TABS, do not have the capability to handle moisture content in the air. Generally, this moisture content or latent load can only be controlled by dehumidifier or sub-mechanical cooling systems, such as a dedicated outdoor air system (DOAS). Therefore, in the worst case scenario, surface condensation can occur when TABS is utilized in areas with humid summer seasons. The green shaded areas in Fig. 10.5 indicate the climatic regions where TABSs have been widely used; the red highlighted regions in Fig. 10.5 represent the climatic regions with a high risk of developing surface condensation while TABS is in operation. These red-shaded areas can also be classified as "Group A: Tropical climates" under the Koppen climate classification with warm and humid summer seasons [5].

Because of this potential risk of occurring surface condensation, radiant cooling systems, including the TABS, are not recommended in the regions with warm and humid summer (red shaded areas in Fig. 10.5). For example, Crown Hall in Chicago requires an automated dehumidification system or dedicated outdoor air system (DOAS) in addition to the radiant cooling panels to prevent surface condensation. Without the dehumidification process, a great amount of moisture coming from Lake Michigan would encounter the cooling panels' cold surface, leading to surface condensation development. As shown in Table 10.1, most of the buildings that adopted TABS are located in climatic regions with less humid summer; the rest are located in areas with warm and often humid summer seasons [5].

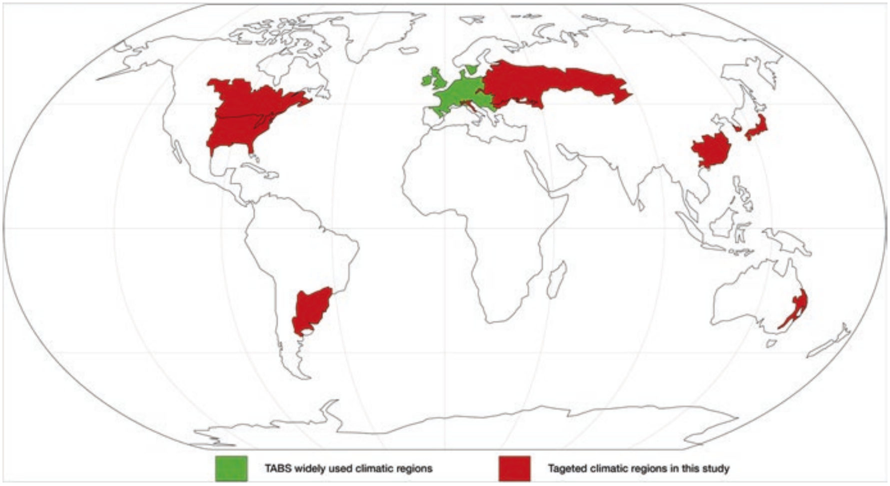


Fig. 10.5 TABS condensation safe climatic regions vs. TABS condensation high-risk regions

When the surface condensation sneaks into internal building construction layers and this interstitial moisture cannot escape from the building construction layers and accumulates, moisture starts to collect and cause moisture-related problems, including corrosion of the building fabric, deterioration of insulation, etc. [14]. Mold is the most critical of these problems (Fig. 10.6). Based on [15], under ideal conditions (optimal temperature and level of humidity), it takes 24–48 hours for mold to germinate and grow [16]. Suppose this mold growth continues for a certain period. In that case, the building construction layers will decay, or in some cases, the mold can extend to interior surfaces, which can lead to occupants' health problems, such as allergic rhinitis. Due to these condensation-driven problems, the potential risk of developing surface condensation keeps thermo-active building systems (TABSs) from being widely adopted in buildings situated in partly warm and humid climate regions [5].

In summary, thermo-active buildings systems (TABSs) are a promising cooling technology in reducing energy demand and providing better thermal comfort for occupants; however, the potential risk of occurring surface condensation on the TABS surface prevents the system to be adopted widely under partly warm and humid climatic regions. Without resolving these surface condensation risks on the TABS, designers and planners will hesitate to adopt the TABS as a primary cooling system for their projects.

Table 10.1 List of TABS-applied buildings with climatic regions

	Project	Location	Climate classification (Koppen Geiger)	Condition in summer
1	Charles Hostler Student Recreation Center	Beirut, Lebanon	Csa, Mediterranean climate	Dry
2	Dolce Vita Tejo	Lisbon, Portugal	Csa, Mediterranean climate	Dry
3	IDOM Company Headquarters	Madrid, Spain	Csa, Mediterranean climate	Dry
4	Fred Kaiser Building	Vancouver, Canada	Csb, Mediterranean climate	Warm and dry
5	Euromed Clinic	Furth, Germany	Cfb, Oceanic climate	Mild
6	Semmelweis Medical University	Budapest, Hungary	Cfb, Oceanic climate	Mild
7	Zollverein School	Essen, German	Cfb, Oceanic climate	Mild
8	Südwestmetall Office Building	Heilbronn, Germany	Cfb, Oceanic climate	Mild
9	Dauerhaft Wandelbar	Stuttgart, Germany	Cfb, Oceanic climate	Mild
10	Wohnhaus	Basel, Switzerland	Cfb, Oceanic climate	Mild
11	Middelfart Savings Bank	Middelfart, Denmark	Cfb, Oceanic climate	Mild
12	Opera House in Copenhagen	Copenhagen, Denmark	Cfb, Oceanic climate	Mild
13	BMW World	Munich, Germany	Cfb, Oceanic climate	Mild
14	Balanced Office Building	Aachen, Germany	Cfb, Oceanic climate	Mild
15	Viborg Town Hall	Viborg, Denmark	Cfb, Oceanic climate	Mild
16	Klarchek Information Commons	Chicago, Illinois, USA	Dfa, Humid continental climate	Warm and often humid
17	Crown Hall	Chicago, Illinois, USA	Dfa, Humid continental climate	Warm and often humid
18	Cooper Union New York	Manhattan, New York, USA	Dfa, Humid continental climate	Warm and often humid
19	Kripalu Housing Tower	Stockbridge, Massachusetts, USA	Dfb, Humid continental climate	Warm and often humid
20	The Terrence Donnelly Center	Toronto, Canada	Dfb, Humid continental climate	Warm and often humid
21	Dockland Offices	Hamburg, Germany	Dfb, Humid continental climate	Warm and often humid
22	Berliner Bogen Offices	Hamburg, Germany	Dfb, Humid continental climate	Warm and often humid
23	Mercedes World	Berlin, Germany	Dfb, Humid continental climate	Warm and often humid
24	Linked Hybrid	Beijing, China	Dwa, Humid continental climate	Hot and often humid

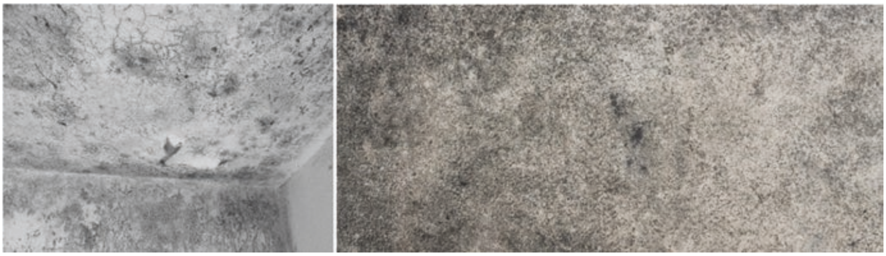


Fig. 10.6 The condensation occurrence and the resultant mold growth on the concrete surfaces

10.3.1 Moisture Movement in Building Construction Layers

While controlling heat transfer through the building envelopes has been the major concern for reducing building cooling and heating energy demand over the past few decades, a moisture-driven problem within the building construction layers has relatively less been considered [17]. The source of this problem is that as designers target increased insulation of the building envelope to achieve higher thermal resistance, there will be an increased temperature differential between the inner and outer portions of the walls; depending on the climate, the inner portion of the wall may get warmer but, at the same time, the outer part will get much colder, or vice versa [18]. Temperature differences in these walls affect the flow of moisture in the wall, a moisture transport process in both vapor and liquid phases, which can lead to interstitial condensation. Thus, special care and attention are required when designers select material and construction layers in envelope systems.

There are mainly four moisture movement mechanisms where the surface condensation development can damage building construction layers: (1) liquid flow by gravity or an air pressure difference, (2) capillary suction through porous materials, (3) air movement, and (4) vapor diffusion. Any moisture-related problem is a consequence of one or a combination of the above-mentioned four mechanisms. The liquid flow is responsible for moving moisture into the building construction layers from the outdoor caused by gravity or an air pressure differential. Capillary suction is a combined effect of the pore size in building construction layers and condensation existence next to it. If the pore size in the construction layers is too small, like concrete material, capillary suction can occur. The moisture can also penetrate the construction layers with air movement. When a crack or gap exists in the construction layers, the infiltration can bring moisture into the layers, which can cause damage to the construction material eventually. Vapor diffusion is the moisture movement in the vapor state through construction layers. This process is driven by a function of the vapor permeabilities of materials and the vapor pressure differential posed across the construction layers. During the vapor diffusion process, when the partial vapor pressure reaches the saturation level, moisture starts to condense within the construction layers [5].

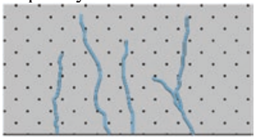
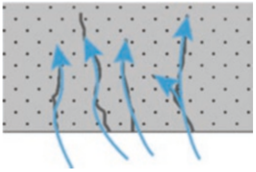
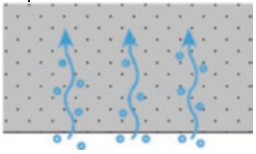
Considering TABS is generally installed on the ceiling side of indoors, the mechanism of liquid flow caused by gravity or an air pressure difference can be disregarded for surface condensation problems of the TABS. Therefore, capillary suction through porous materials, air movement, and vapor diffusion are the three mechanisms of moisture movement that need to be controlled to prevent surface condensation while the TABS is in operation (Table 10.2).

Capillary suction brings moisture into porous materials mainly. If the pore size in a material is small enough (e.g., concrete, silty clay, etc.), the capillary suction occurs. Capillary suction never occurs in material without pores (e.g., glass, steel, plastics, etc.) [5].

In general, capillary suction can be controlled by blocking off the capillary moisture or selecting relatively large pore size of the building construction materials. Capillary suction can also be prevented by sealing the connections between materials using caulking joints or providing the links wide enough not to cause capillary effect [5].

Air movement mechanisms can transport moisture into building construction layers both from the conditioned indoor space and the exterior. Following three conditions should be satisfied to let moisture into the building construction layers with an air movement mechanism: (1) moist air should exist, (2) a gap or an opening exists in the building construction layers, and (3) an air pressure difference occurs across space in the building construction layers [5].

Table 10.2 Three mechanisms of moisture movement while TABS operation

Moisture transfer pathways	Description
Capillary suction 	Capillary suction is a combined effect of the pore size in building construction layers and condensation existence nearby. If the pore size in the construction layers is small, like concrete material, the capillary suction effect can be significant.
Air movement 	The moisture can also penetrate the construction layers via air movement. When a crack or gap exists in the construction layers, the air can bring moisture deep into the layers, which can cause severe damage to the construction material.
Vapor diffusion 	Vapor diffusion is the movement of moisture in the vapor state through construction layers.

Even if the moisture enters the building construction layers, it does not necessarily deposit along with the building construction layers; the air movement's velocity should be slow enough for the moist air to be cooled down to the dew point temperature, which in turn leads to the surface condensation development. Otherwise, the fast-flowing moist air can be maintained above the dew point. Making the building envelope airtight is one of the most effective strategies to deal with moisture transfer through the air movement mechanism [5].

Vapor diffusion is the moisture movement process in the vapor state through materials. As far as the vapor pressure difference exists between indoors and outdoors, vapor diffusion occurs. In a cold climate where a building is mainly heated, vapor diffusion typically moves moisture from the indoor conditioned room into building construction layers. In contrast, in warm weather, the vapor diffusion naturally moves moisture from the exterior into the building construction layers [5].

Considering these three potential moisture transfer pathways together, the total amount of moisture transferred from the indoor space or the exterior into the building construction layers can be computed, thus enabling the prediction in the surface condensation occurrence while TABS is in operation. With this information, the potential risk of developing surface condensation can be estimated and controlled to prevent the construction material's damage [5].

10.3.2 Dynamic Modeling of Heat and Moisture Transfer in Building Construction Layers

Fourier's law is a basis for the heat transfer model, while Fick's law and Darcy's law are used for the moisture transfer model and liquid flow model, respectively [19].

Fourier's law (for heat transfer):

$$\dot{q} = -k\frac{\partial T}{\partial x} \tag{10.1}$$

where $\dot{q}$ is the heat flux, k is the thermal conductivity of the material, T is temperature, and x is the length of the material.

Fick's law (for vapor diffusion):

$$\dot{m}_{\mathrm{v}} = -\mu\frac{\partial P_{\mathrm{v}}}{\partial x} \tag{10.2}$$

where $\dot{m}_{\mathrm{v}}$ is the mass flux for vapor, μ is the vapor permeability, and P_{v} is the water vapor pressure.

Darcy's law:

$$\dot{m}_{1} = K\frac{\partial P_{1}}{\partial x} \tag{10.3}$$

where $\dot{m}_l$ is the mass flux for liquid water, K is the hydraulic conductivity, and P_l is the capillary pressure.

The overall moisture balance is given by

$$\frac{\partial}{\partial x}\left(\mu\frac{\partial P_v}{\partial x}\right)-\frac{\partial}{\partial x}\left(K\frac{\partial P_l}{\partial x}\right)=\rho\frac{\partial w}{\partial t} \tag{10.4}$$

Because there is no energy generation in the system, the significant energy flows are heat conductivity and enthalpy flow via liquid water transfer and vapor transfer. Thus, the mass and energy conservations are obtained by using Fick's law, Darcy's law, and Fourier's law:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+h(T)\frac{\partial}{\partial x}\left(\mu\frac{\partial P_v}{\partial x}\right)=\frac{\partial T}{\partial t}\rho\left(C_{p,d}+wC_{p,l}\right) \tag{10.5}$$

Equations (10.4) and (10.5) are the governing equations; they need to be solved to predict heat and moisture transfer in building construction layers. For a numerical solution, vapor diffusion and capillary transfer equations need to be decoupled and are given as

$$\frac{\partial}{\partial x}\left(\mu\frac{\partial P_v}{\partial x}\right)=-\frac{\partial \dot{m}_v}{\partial x}=\rho\frac{\partial w_v}{\partial t} \tag{10.6.a}$$

$$\frac{\partial}{\partial x}\left(K\frac{\partial P_l}{\partial x}\right)=-\frac{\partial \dot{m}_l}{\partial x}=\rho\frac{\partial w_l}{\partial t} \tag{10.6.b}$$

$$w=w_v+w_l \tag{10.6.c}$$

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+h(T)\frac{\partial}{\partial x}\left(\mu\frac{\partial P_v}{\partial x}\right)=\rho\left(C_{p,d}+wC_{p,l}\right)\frac{\partial T}{\partial t} \tag{10.6.d}$$

The last step for dynamic modeling of building construction layers is identifying a correlation between the surface temperature of the concrete layer and the supply water temperature for the TABS. The surface temperature for concrete materials can be calculated from a supply water temperature using Eqs. (10.7) and (10.8) [19]. When the thickness of the slab is two L, and its initial temperature of T_1 is cooled with the fluid temperature of T_∞, a numerical solution is available for the temperature T at a location and time t [20].

$$Y=Y_0 f\left(b_1 n\right) \tag{10.7}$$

where

$$Y = \frac{T - T_\infty}{T_1 - T_\infty}$$

$$Y_0 = \frac{T_0 - T_\infty}{T_1 - T_\infty} = c_1 \exp\left(-b_1^{\,2} F_o\right)$$

$n = x/L$, x= a distance from the midplane of the slab of thickness $2L$ cooled on both sides,

b_1, c_1= the coefficients that are functions of the Biot number, $F_o = at/L^2$, $a = k/\rho C_p$.

$$f\left(b_1 n\right) = \cos\left(b_1 n\right) \qquad c_1 = \frac{4\sin\left(b_1\right)}{2b_1 + \sin\left(2b_1\right)} \tag{10.8}$$

Therefore, if we set $x = L$ and $T = T_{sf}$, we can calculate the surface temperature of the TABS concerning the fluid temperature.

10.3.3 Building Construction Condensation Prediction Models

Since the 1930s, numerous studies have explored ways to model heat and moisture (hygrothermal) transfer in building construction layers. Rodgers [21] was the very first to research vapor pressure as a driving potential for moisture transfer. In the study, Rogers presented the vapor pressure curves method, which shows the relative partial vapor pressure level across building construction layers. Rowley et al. [22, 23] then refined the existing work into the prevailing theory of vapor diffusion models by adopting heat conduction principles. Vos and Coleman [24] further developed the models by attesting the combined effect of vapor diffusion and capillary suction on moisture transfer. Later, Künzel and Grosskinsky [25] identified air transport as an additional driving potential for moisture transfer. The Luikov model [26] and the Philip and de Vries model [27] are the most widely used hygrothermal transfer models; these adopt the temperature and the moisture content as driving potentials. However, taking the moisture content as the moisture transfer potential sometimes makes the models challenging because the moisture content level is not always continuous across the building construction layers [28]. Therefore, Y. Liu et al. [29] proposed the constant relative humidity instead of the moisture content as the driving potential for moisture transfer to deal with this problem. With these modifications, the researchers have developed the hygrothermal transfer models in a way that incorporates the three hygrothermal pathways in building construction layers while simplifying the solution for the models by adopting continuous parameters. The results provided by the models predict short-term condensation with reasonable accuracy in building construction layers.

Despite their usefulness, these models are not directly applicable for controlling the surface condensation of TABS for two reasons. First, a short-term condensation prediction from the existing model is insufficient for dealing with dynamic indoor condition changes. Indoor conditions do not remain stable but fluctuate according to daily weather changes [30]. Because of this dynamic indoor condition change, the risk of surface condensation sometimes can increase rapidly, which in turn can lead to a sudden development of surface condensation, even though the model has calculated the ongoing risk. Second, the model's short-term condensation estimation can sometimes cause severe prediction errors for buildings with heavy construction materials like concrete. The hygrothermal transfer rate of building construction layers is delayed due to the construction materials' high heat capacity; this time delay can sometimes last up to almost half a day. Because of less accurate condensation prediction caused by the slow and gradual hygrothermal transfer in heavy construction materials, direct application of these models can be inadequate for enabling a system to control surface condensation.

Thus, given the dynamic daily fluctuation in indoor conditions and the time delay in the hygrothermal response of heavy concrete materials, an estimation that anticipates the surface condensation at least a few hours ahead is required for more accurate surface condensation control. With a few hours-ahead assessment, both the indoor condition changes and the time delay in the hygrothermal transfer can be considered altogether in advance, providing a more accurate condensation prediction for the system to make a better decision.

10.3.4 Model Predictive Control-Based Condensation Prediction

A promising approach for surface condensation control is model predictive control (MPC) among rigid control approaches. In contrast to other rule-based controllers, such as two-position or modulating controls, MPC determines the input signal for the system not based on just the current states but also on the impact the actions will have on the future conditions (Fig. 10.7). Because MPC considers both current states and future states, it is suitable for anticipatory surface condensation control capable of dealing with dynamic indoor condition changes and the time delay in hygrothermal transfer in advance [14].

The classical objective function utilized by the MPC is given as [31]

$$J\left(t_k\right)=\sum_{i=N_1}^{N_y}\mathbf{w}_y(i)\left[\hat{y}\left(t_k+i\right)-y_{\text{set}}\left(t_k+i\right)\right]^2+\sum_{i=N_1}^{N_u}\mathbf{w}_u(i)\left[u\left(t_k+i\right)-u\left(t_k+i-1\right)\right]^2 \tag{10.9}$$

where

t_k = control time-step
y_{set} = set point, $\hat{y}$ = predicted output
u = command effort

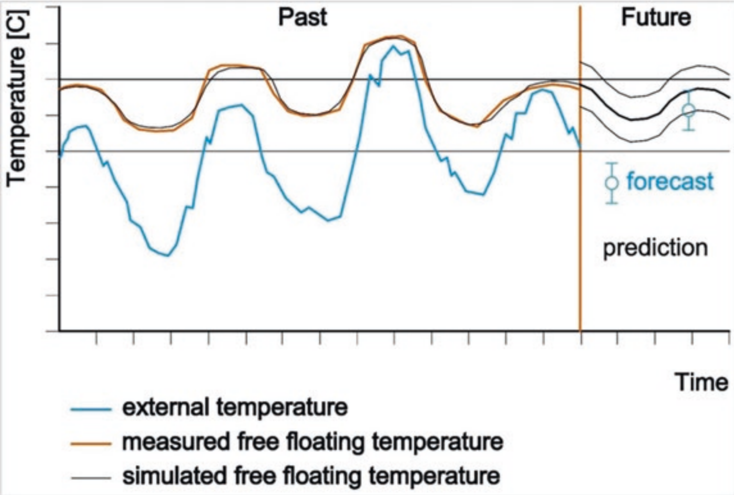


Fig. 10.7 Conceptual diagram of model predictive control for temperature

N_y = the prediction horizon where the output error
$\hat{y} - y_{set}$ is minimized
N_u = the control horizon where the effort increment is minimized
ω_y = weighting factor for prediction error
ω_u = weighting factor for command effort

An initial application of the MPC started in the late 1970s in the process industries in chemical plants and oil refineries [32]. Since then, the MPC has been adopted in autoclave composite processing, wastewater treatment, automotive industry, etc. In autoclave composite processing, the MPC is assumed to define an optimal input to determine a bagging procedure and a cure cycle that assures cost efficiency [33]. For the wastewater treatment process, input parameters of aeration rate, dilution rate, and recycled ratio are adjusted to achieve a specific concentration level of dissolved oxygen by repeatedly rejecting the water's substrate concentration [33].

Recently, MPC has been studied widely in the built environment because of significant time and cost reduction in data processing. The majority of MPC research is primarily focused on HVAC system control [34–37], building thermal behavior predictions [38, 39], or indoor thermal comfort control [40–42]. However, there are few studies in which MPC was applied to control the surface condensation on building construction layers.

The basic framework of MPC for HVAC systems is shown in Fig. 10.8. It is a closed-loop cycle consisting of a dynamic model and optimizer [43]. The dynamic model simulates several potential future states using adjustments in the control inputs. The best control input that minimizes an objective function without penalizing the constraints is found using the optimizer [44]. When the best control input is determined, it is fed back into the HVAC system operation. This process is repeated for every control horizon [11].

The MPC objective function that ensures thermal comfort with minimum cooling energy is [31]

$$\begin{aligned} &minimize: \ J(t_k) = \sum_{i=1}^{N_u} u(t_k + i) \quad \text{Objective function} \\ &\text{subject to}: \ 0 \le u(t_k + i) \le u_{\max}, \quad i = 1 \ldots N_u \quad \text{Constraints} \\ &\hat{y}(t_k + i | t_k) \le y_{\max}(t_k + i), \ i = 1 \ldots N_y \end{aligned} \tag{10.10}$$

where t_k = control time-steps, N_u = the number of steps in the future horizon, $u(t)$ = system inputs, $u_{\max}$ = the maximum cooling system input, $\hat{y}(t)$ = system outputs, and $y_{max}(t)$ = upper indoor temperature threshold for thermal comfort.

After dynamic model predicts several potential future states, MPC determines the best control scenario under the objective function and the constraints [45]. At every control time-step, the control problem for MPC is formulated and solved to meet the objective without violating the control horizon's restrictions. When the best control input is determined under the control horizon, the best control input is fed back into the system operation and moves forward to the next control time-step (Fig. 10.9).

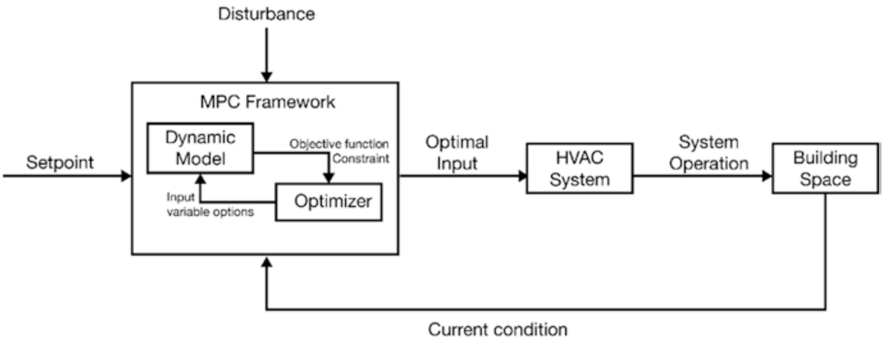


Fig. 10.8 The basic framework of model predictive control for HVAC systems

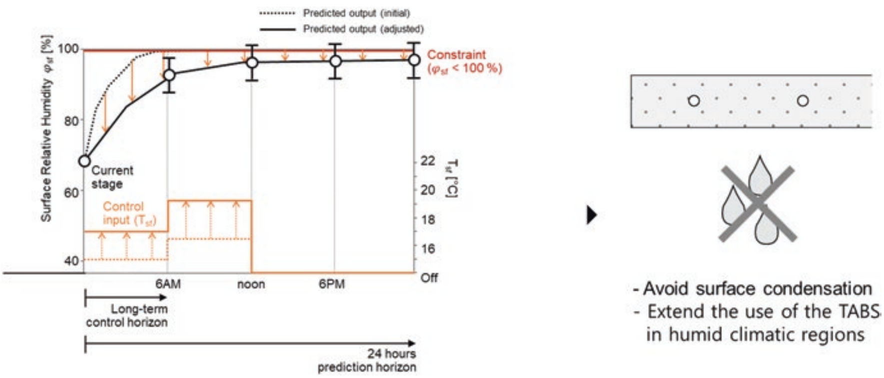


Fig. 10.9 Surface condensation control with MPC

10.4 Conclusions

Hydronic-based radiant cooling systems have been widely used for their energy efficiency and providing better thermal comfort for occupants when compared to conventional convection-based cooling systems. However, due to the potential risk of developing condensation on the surface prevents hydronic-based radiant cooling systems, including thermo-active building systems (TABS), from being applied in buildings located in warm and humid climate regions [14].

Throughout this chapter, a framework to prevent surface condensation while TABS is in operation was introduced. Because the MPC-based surface condensation prevention framework can continually control the surface condensation risk when the TABS is in operation, potential damage to the building construction layers can be avoided. Avoidance of this damage in building envelopes will extend the repair cycle for each building construction layer, which in turn can lead to overall maintenance cost savings for buildings [14].

The MPC-based surface condensation control can also resolve mold growth-driven health problems like allergic rhinitis. With several hours ahead of surface condensation prediction by the MPC framework, the potential risk of failing to detect surface condensation can be eliminated, which will contribute to the prevention of mold growth in building construction layers [14].

Additionally, MPC-based surface condensation prevention will broaden the adoption of the TABS even in warm and humid climate regions. Given the growing demand for the TABS [46], the MPC clearly satisfies an important need of building industry. By controlling the potential risk of surface condensation development, it can extend the use of the TABS to areas in which climate conditions have made them infeasible [14].

References

1. ASHRAE, ANSI/ASHRAE Standard 55. (2010). *Thermal environmental conditions for human occupancy*.
2. Shi, H., & Chen, Q. (2021). Building energy management decision-making in the real world: A comparative study of HVAC cooling strategies. *Journal of Building Engineering, 33*, 101869.
3. ASHRAE. (2017). *ASHRAE handbook – Fundamentals*. ASHRAE.
4. Meierhans, R. A. (1996). Room air conditioning by means of overnight cooling of the concrete ceiling. *ASHRAE Transactions, 102*, 693–697.
5. Woo, D. (2021). *Model predictive control-based surface condensation prevention for thermo-active building systems (TABS): In regard to the partial theoretical model approach* (Doctoral dissertation).
6. Uponor. (2013). *Radiant cooling design manual, embedded systems for commercial applications*. Uponor.
7. Schmelas, M., Feldmann, T., & Bollin, E. (2015). Adaptive predictive control of thermo-active building systems (TABS) based on a multiple regression algorithm. *Energy and Buildings, 103*, 14–28.

8. ASHRAE, ANSI/ASHRAE Standard 62.1. (2016). *Ventilation for acceptable indoor air quality*.
9. Olesen, B. (2012). Thermo active building systems using building mass to heat and cool. *ASHRAE Journal, 54*, 44–52.
10. Babiak, J., Olesen, B. W., & Petrás, D. (2009). *Low-temperature heating and high-temperature cooling*. REHVA.
11. Romaní, J., de Gracia, A., & Cabeza, L. F. (2016). Simulation and control of thermally activated building systems (TABS). *Energy and Buildings, 127*, 22–42.
12. Kalogirou, S. A., Florides, G., & Tassou, S. (2002). Energy analysis of building employing thermal mass in Cyprus. *Renewable Energy, 27*, 353–368.
13. Moe, K. (2010). *Thermally active surfaces in architecture*. Princeton Architectural Press.
14. Woo, D., & Junghans, L. (2020). Framework for model predictive control (MPC)-based surface condensation prevention for thermo-active building systems (TABS). *Energy and Buildings, 215*, 109898.
15. U.S. Department of Homeland Security FEMA. (2008). *Dealing with mold and mildew in your flood-damaged home*.
16. Bellia, L., & Minichiello, F. (2003). A simple evaluator of building envelope moisture condensation according to a European Standard. *Building and Environment, 38*, 457–468.
17. Karagiozis, A. N., Lstiburek, J., & Desjarlais, A. (2007). Scientific analysis of vapor retarder recommendations for wall systems constructed in North America. *ASHRAE Journal*. In Proceedings of the Thermal Performance of the Exterior Envelopes of Whole Buildings XI International Conference, Clearwater Beach, FL, USA, 5–9 (2010).
18. Arends, T., Ruijten, P., & Pel, L. (2020). Moisture-induced bending of an oak board exposed to bilateral humidity fluctuations. *Journal of Building Engineering, 27*, 100957.
19. Bacher, P., & Madsen, H. (2011). Identifying suitable models for the heat dynamics of buildings. *Energy and Buildings, 43*, 1511–1522.
20. Prívara, S., Cigler, J., Váňa, Z., Oldewurtel, F., Sagerschnig, C., & Žáčeková, E. (2013). Building modeling is a crucial part of building predictive control. *Energy and Buildings, 56*, 8–22.
21. Rodgers, T. S. (1938). Preventing condensation in insulated structures. *Architectural Record, 83*, 109–119.
22. Rowley, F. B. (1939). *A theory covering the transfer of vapour through materials*. ASHVE trans.
23. Rowley, F. B., Algren, A. B., & Lund, C. E. (1939). *Condensation of moisture and its relation to building construction and operation*. ASHVE Trans.
24. Vos, B. H., & Coleman, E. (1967). *Condensation in structures*. Report nr BI–67–33/23. TNO–IBBC
25. Künzel, H. M. (1995). *Simultaneous heat and moisture transport in building components: One- and two-dimensional calculation using simple parameters*. IRB-Verlag.
26. Luikov, A. V. (1966). *Heat and mass transfer in capillary-porous bodies*. Pergamon Press.
27. Philip, J. R., & de Vries, D. A. (1957). Moisture movement in porous materials under temperature gradients. *Transactions of the American Geophysical Union, 38*, 222–232.
28. Antonopoulos, K. A., & Tzivanidis, C. (1997). Numerical solution of unsteady three-dimensional heat transfer during space cooling using ceiling-embedded piping. *Energy, 22*, 59–67.
29. Liu, Y., Wang, Y., Wang, D., & Liu, J. (2013). Effect of moisture transfer on internal surface temperature. *Energy and Buildings, 60*, 83–91.
30. Petersen, S., & Bundgaard, K. W. (2014). The effect of weather forecast uncertainty on a predictive control concept for building systems operation. *Applied Energy, 116*, 311–321.
31. Hazyuk, I., Ghiaus, C., & Penhouet, D. (2012). Optimal temperature control of intermittently heated buildings using Model Predictive Control: Part II – Control algorithm. *Building and Environment, 51*, 388–394.
32. Xi, Y., Li, D., & Lin, S. (2013). Model predictive control – Status and challenges. *Acta Automatica Sinica, 39*(3), 222–236.

33. Caraman, S., Sbarciog, M., & Barbu, M. (2007). Predictive control of a wastewater treatment process. *International Journal of Computers, Communications, and Control, 2*(2), 132–142.
34. Huang, H., Chen, L., & Hu, E. (2015). A new model predictive control scheme for energy and cost savings in commercial buildings: An airport terminal building case study. *Building and Environment, 89*, 203–216.
35. Yu, Y., Loftness, V., & Yu, D. (2013). Multi-structural fast nonlinear model-based predictive control of a hydronic heating system. *Building and Environment, 69*, 131–148.
36. Spindler, H. C., & Norford, L. K. (2009). Naturally ventilated and mixed-mode buildings Part II: Optimal control. *Building and Environment, 44*, 750–761.
37. May-Ostendorp, P., Henze, G. P., Corbin, C. D., Rajagopalan, B., & Felsmann, C. (2011). Model-predictive control of mixed-mode buildings with rule extraction. *Building and Environment, 46*, 428–437.
38. Zhang, X., Tan, S., & Li, G. (2014). Development of an ambient air temperature prediction model. *Energy and Buildings, 73*, 166–170.
39. Morosan, P. D., Bourdais, R., Dumur, D., & Buisson, J. (2010). Building temperature regulation using a distributed model predictive control. *Energy and Buildings, 42*, 1445–1452.
40. Freire, R. Z., Oliveira, G. H. C., & Mendes, N. (2008). Predictive controllers for thermal comfort optimization and energy savings. *Energy and Buildings, 40*, 1353–1365.
41. Ascione, F., Bianco, N., de Stasio, C., Mauro, G. M., & Vanoli, G. P. (2016). Simulation-based model predictive control by the multi-objective optimization of building energy performance and thermal comfort. *Energy and Buildings, 111*, 131–144.
42. Álvarez, J. D., Redondo, J. L., Camponogara, E., Normey-Rico, J., Berenguel, M., & Ortigosa, P. M. (2013). Optimizing building comfort temperature regulation via model predictive control. *Energy and Buildings, 57*, 361–372.
43. Li, X., & Wen, J. (2014). Review of building energy modeling for control and operation. *Renewable and Sustainable Energy Reviews, 37*, 517–537.
44. Široky, J., Oldewurtel, F., Cigler, J., & Prívara, S. (2011). Experimental analysis of model predictive control for an Energy efficient building heating system. *Applied Energy, 88*, 3079–3087.
45. Oldewurtel, F., Parisio, A., Jones, C. N., Gyalistras, D., Gwerder, M., Stauch, V., Lehmann, B., & Morari, M. (2012). Use of model predictive control and weather forecasts for Energy efficient building climate control. *Energy and Buildings, 45*, 15–27.
46. TechNavio. (2018). *Global radiant heating and cooling systems market 2018–2022*.