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Study on dynamic thermal characteristics of thermoelectric radiant cooling panel system through a hybrid method

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ABSTRACT

Thermoelectric radiant panel system (TERP), requires no hydronic pipes, pumps and chillers and the size is compact in solid form. In this study, the main results include a new system model of TERP and some new findings on the system dynamic characteristics. The new model integrates finite difference method and state-space matrix, which is an integration of great simulation accuracy, high speed, and easy implementation. The thermal response time (TRT) and its asynchronism are confirmed and a new concept of AM (Asynchronism Magnitude) is defined to measure the degree of TRT asynchronism. Some new observations are obtained: (1) Under a certain environment, AM becomes a constant even when different step changes of current are imposed; (2) The TRT asynchronism disappeared at the second stage when environmental condition is step changed. Three new definitions of TRT are proposed and compared. Finally, in order to realize the fast and accurate prediction of TRT for the use of system on-line control or fast evaluation under dynamic state, an artificial neural network-based model is proved to be effective. The dynamic analysis can offer a new paradigm to the evaluation, control and optimization of radiant cooling and other dynamic systems.

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1. Introduction

Since December of 2019, an increasing number of cases of novel coronavirus (2019-nCoV)—infected pneumonia (NCIP) have been identified in Wuhan, China [1,2], which then spread to the rest of the country. It was reported that in the hospitals of Wuhan, nearly all the air conditioning systems are shut off to prevent cross infection and spread of virus through air conditioning system. Under spotlight of this severe circumstance, radiant conditioning systems are showing their advantages, because radiant system can remove/provide heat with no need of producing cooled/heated air. The radiant floor [3], ceiling [4] or walls [5] are contributing to a better artificial controlled indoor space with high reliability.

In order to better serve for indoor thermal environment control, there are some inherent shortcomings with radiant systems especially radiant cooling panels, including surface water condensation risk, inconvenient control of cool water flow for system operation, insufficient cooling capacity comparing with air cooling systems, etc.

It is noticed that the issues related energy supply [6–8] and surface condensation [9,10] of radiant cooling system are meeting with novel and suitable solutions [11], but all those mentioned systems are functioned with hydronic pipes for cooling energy delivery. Thus, the difficulties related to water flow control and system response time delay remain. Confronted with this problem, a kind of solid based thermoelectric radiant cooling panel system (TERP) was proposed and investigated. The earliest study was conducted by Lertsatitthanakorn experimentally in a full-sized chamber [12]. Then Liu et al. [13,14] developed this system by incorporating displacement ventilation system for performance enhancement and also applied to a radiant wall system using solar energy as driven power. Before Luo et al. [15,16] built a complex analytical model for system heat transfer simulation, simplified thermal evaluation method [17,18] was adopted for initial analysis of the system. In addition, this thermoelectric radiant cooling system was then showing its application potential in high-speed train cabins [19], and the water condensation issue was handled with assistance of liquid desiccant system [20]. Due to the unique features of fast cooling, free from mechanical structure, operation...
noise free, and no use of refrigerant [21,22], the control and commission of thermoelectric module (TEM) could be much easier than conventional hydronic radiant systems.

Considering the wide application potential and the increasing research interest on the thermoelectric radiant cooling systems, some fundamental scientific problems remain unsolved which hinders system development:

1. An accurate, fast, and easy-implemented system heat transfer model is still missing. In some previous studies, researchers have contributed their effort to either simplified one-dimensional model or complicated analytical three-dimensional model, but none of them can meet all the requirements of detailed temperature field simulation, easy-implementation-revision of model, as well as fast calculation speed. On one end, the earliest model neglected the non-uniform surface temperature distribution of TERP [17,18], which may result in some errors in the model based performance analysis. One the other end, the strictly derived two-dimensional and even three-dimensional fully analytical model can reveal the details of the physical and thermal features of TERP with explicit expression [15,16], but those equations are involved with summation of multiple series with multiple integrals. Especially, the calculation of current temperature field needs dynamic information of past several time nodes. The calculation sometimes is slowed down due to those reasons. Meanwhile, the finite difference method [23] or finite volume method [24] was proposed for system simulation, but they become inconvenient when solving difference differential algebraic equations and when the boundary conditions are changed. The model of TERP should be updated with new solutions, so that it can serve for further applications.

2. The complex dynamic thermal response characteristics of thermoelectric radiant cooling system (TERP) is still unknown. It is noted that in order to control surface condensation as well as the cooling capacity of the radiant ceiling panels, the dynamic temperature change features of radiant ceiling panel surface must be fully understood [25]. Based on ANSYS numerical model, Jin et al. [25] investigated how the surface temperature of radiant ceiling varied with increasing or reducing supply cool water temperature. Through conducting experimental study, Sun et al. [26,27] tested the response time of the newly proposed radiant system and concluded that under cooling conditions, the dynamic response time is not significantly correlated with the other variables. However, majority of studies on radiant cooling systems are more concerned with system efficiency and cooling capacity, resulting in limited understanding on system dynamic thermal response characteristics for system control. The researches on TERP confronted with the same problem based on literature analysis.

3. How the dynamic thermal response TERP can be adequately described and quantitatively evaluated? Is the conventional Thermal Response Time (TRT) suitable for TERP? Thermal response time (TRT) is widely used in many systems, including photovoltaic panel temperature evaluation [28], thermal performance of heat pipe [29], or even building heating systems [30]. As for the radiant panel systems, according to the summary by Ning et al. [31], “response time” and “time constant” are two widely used expressions for the evaluation of the dynamic thermal performance of radiant systems. But there is no clear definition or description of the two parameters in radiant systems. When the TERP is concerned, the effectiveness of conventional concept of TRT is in doubt because of the system uniqueness. At the same time, we noticed that machine learning method such as artificial neural network has been showing its power in solving some difficult problems that conventional is incapable or ineffective. The machine learning methods are found to be highly powerful for building energy prediction [32,33], and some researches starts using ANN for thermoelectric based system evaluation [34] or thermoelectric generator [35]. However, very few has shown its application for radiant cooling systems. Even there is very limited studies showcased the application of ANN for radiant heating systems [36].

Based on the mentioned three aspects of scientific gaps, in this study, an explicit matrix solution is derived for the dynamic heat transfer modeling of TERP with required simulation accuracy, fast calculation speed and easy-implementation in programming. Based on the newly proposed model, an in-depth investigation was conducted for discussing a series of important topics about TRT of TERP. In addition, a new definition of TRT was proposed, followed by Taguchi experimental test on the impact factors of TRT based on sign-to-noise ratio. And a machine learning based method was adopted for predicting TRT, which lay down a practical foundation for TERP control and further development.

2. Methodology and modeling

2.1. System description

An experimental chamber was built for the study of thermoelectric radiant panel (TERP) system, ten chips of TEMs (module type is 9500/127/060B and \( I_{\text{max}} = 6A \), \( V_{\text{max}} = 17.6V \), \( \Delta T_{\text{max}} = 72K \), \( Q_{\text{max}} = 57.0W \), Dimension: 39.7 mm × 39.7 mm × 4.16 mm) were installed uniformly and sparsely on the back surface of an aluminum radiant panel. Fig. 1 shows the location and arrangement of those TEMs. In the internal electrical circuit, five of TEMs are connected in series and two groups of TEMs are connected in parallel by electric leads. The entire aluminum panel (1580 mm × 810 mm) was surrounded by insulation material at around corner as well as the back for the prevention of heat loss. A typical region is marked by a dashed square in Fig. 1 that is the target modeling region in the following equations. The dimension of the typical region is 405 mm (length) × 316 mm (width) × 2 mm (thickness).

In side view of TERP, the working mechanism can be clearly expressed. Once the TEM was triggered by direct current from an independent DC power source, the TEM will immediately absorb heat from the radiant panel and transfer to the air duct. Therefore, the TERP can be cooled and provide convective and radiative cooling to the indoor space.

2.2. Dynamic state modeling

The basic modeling strategy is discrete the governing heat transfer equation into a set of linear algebraic equations and the parameters and unknow variables for next calculation time point are rearranged as a decent matrix equation. Then the solution can be easily expressed as inverse of matrix and dot product between matrix and vector.

Fig. 2 shows the sub-typical region which is a quarter of the original region. Three temperature sensors (T1, T2, T3) were placed on the front surface of radiant panel to measure and record the dynamic surface temperatures. Taking the position of TEM as the origin of X–Y coordinate and assume that Lx and Ly are the length on each side. In order to evaluate the surface two-dimensional
temperature field, a structured mesh is adopted and displayed in Fig. 2. There are \( n_x \) points in the horizontal axis and \( n_y \) points in the vertical axis. The space step at two direction is \( dx \) and \( dy \). The thickness of the radiant panel is \( dz \). The location of each point can be expressed as \((i, j)\). For each point in the grid, a heat transfer balance equation can be established. As Lim et al. [23] noted that, the heat transfer equation for heat source area and the other area is different, which are respectively depicted by Eq. (1) and Eq. (2), where \( \rho \) and \( C \) and \( \lambda \) are the density and thermal capacitance and thermal conductivity of aluminum panel and \( \sigma \) is thermal diffusivity; \( T \) is the surface temperature of aluminum panel; \( T_{in} \), \( T_{MRT} \) and \( T_f \) represent respectively indoor air temperature, indoor mean radiant temperature and air temperature in the upper air duct; \( h_c \), \( h_r \) and \( h_b \) represent respectively convective heat transfer coefficient, radiative heat transfer coefficient, and comprehensive heat transfer coefficient between the panel and air in the upper duct; \( q_c \) means the heat flux density of TEM.

\[
\frac{1}{\rho Al} \frac{\partial T}{\partial t} = \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + \frac{h_c}{\lambda Al} dz (T_{in} - T) + \frac{h_r}{\lambda Al} dz (T_{MRT} - T) + \frac{q_c}{\lambda Al} dz
\]

\[ (1) \]

\[
\frac{1}{\rho Al} \frac{\partial T}{\partial t} = \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + \frac{h_c}{\lambda Al} dz (T_{in} - T) + \frac{h_r}{\lambda Al} dz (T_{MRT} - T) + \frac{h_r}{\lambda Al} dz (T_f - T)
\]

\[ (2) \]

It should be noted that the radiative heat transfer with fourth power of surface temperature expression is replaced by a linear expression for easier integration and the coefficient \( h_r \) is given by Eq. (3), where \( \varepsilon \) is the panel surface emissivity and \( \sigma \) is the Stephan-Boltzmann constant. Besides, the convective heat transfer coefficient \( h_c = \frac{Nu}{\lambda_{air}/L} \) for this study is given by Eq. (4) which has been used by relevant studies for radiant cooling panel systems [37]. The heat transfer on the back side \( h_b \) can be calculated by Eq. (5) [14], where \( u \) is air flow velocity in the upper air channel.

\[
h_r = \varepsilon \sigma \left( \frac{T_{MRT}^2 + T^2}{T_{MRT} + T} \right)
\]

\[ (3) \]

\[
Nu = \frac{C_h \times Ra^{1/n}}{C_h}
\]

\[ (4) \]

\[
h_b = \frac{1}{d_b/\lambda_b + 1/[1.163(10 + 6\sqrt{u})]}
\]

\[ (5) \]
Meanwhile, the heat flux density of TEM is given by \( Q_c/A_{TEM} \) where \( Q_c \) is the cooling capacity of TEM and \( A_{TEM} \) is the module area. The heat flux at cooling side \( Q_c \) and heating side \( Q_h \) of TEM are given by Eq. (6) and Eq. (7), where \( \alpha \) is Seebeck coefficient; \( I \) is working current; \( k \) is thermal conductivity of TEM; \( R \) is the electric resistance; \( T_c \) and \( T_h \) are respectively temperature at cool and hot side of TEM.

\[
Q_c = \alpha I T_c - k (T_h - T_c) - \frac{1}{2} I^2 R
\]  
\[
Q_h = \alpha I T_h - k (T_h - T_c) + \frac{1}{2} I^2 R
\]

Based on the guide of Fig. 2 and the governing equations of (1) and (2), the equation set for entire calculation domain can be determined. For the sake of clear presentation, only the equations of some representative points are to be given below, but this does not influence the derivation of the final explicit solution.

For the heat source point at (1,1):

\[
\frac{1}{\alpha_{Al}} \frac{d}{dt} T_{n+1}^{(1,1)} - T_n^{(1,1)} \]
\[
= \begin{cases} 
\frac{2}{dx} \left( T_n^{(1,1)} - T_{n+1}^{(1,1)} \right) + \frac{2}{dy} \left( T_n^{(1,1)} - T_{n+1}^{(1,1)} \right) \\
+ \frac{h_c}{\lambda_{Al} dz} \left( T_m - T_{n+1}^{(1,1)} \right) + \frac{h_r}{\lambda_{Al} dz} \left( T_{MRT} - T_{n+1}^{(1,1)} \right) + \frac{q_c}{\lambda_{Al} dz} 
\end{cases}
\]

(8)

For the boundary point at (1,2):

\[
\frac{1}{\alpha_{Al}} \frac{d}{dt} T_{n+1}^{(1,2)} - T_n^{(1,2)} \]
\[
= \begin{cases} 
\frac{1}{dx} \left( T_n^{(1,1)} + T_{n+1}^{(1,2)} - 2T_{n+1}^{(1,2)} \right) + \frac{2}{dy} \left( T_n^{(1,2)} - T_{n+1}^{(1,2)} \right) \\
+ \frac{h_c}{\lambda_{Al} dz} \left( T_m - T_{n+1}^{(1,2)} \right) + \frac{h_r}{\lambda_{Al} dz} \left( T_{MRT} - T_{n+1}^{(1,2)} \right) + \frac{h_b}{\lambda_{Al} dz} \left( T_f - T_{n+1}^{(1,2)} \right) 
\end{cases}
\]

(9)

For the inner point at (2,2):

\[
\frac{1}{\alpha_{Al}} \frac{d}{dt} T_{n+1}^{(2,2)} - T_n^{(2,2)} \]
\[
= \begin{cases} 
\frac{1}{dx} \left( T_n^{(2,1)} + T_{n+1}^{(2,2)} - 2T_{n+1}^{(2,2)} \right) + \frac{1}{dx} \left( T_n^{(1,2)} + T_{n+1}^{(2,2)} - 2T_{n+1}^{(2,2)} \right) \\
+ \frac{h_c}{\lambda_{Al} dz} \left( T_m - T_{n+1}^{(2,2)} \right) + \frac{h_r}{\lambda_{Al} dz} \left( T_{MRT} - T_{n+1}^{(2,2)} \right) + \frac{h_b}{\lambda_{Al} dz} \left( T_f - T_{n+1}^{(2,2)} \right) 
\end{cases}
\]

(10)

For the boundary point at (2,1):

\[
\frac{1}{\alpha_{Al}} \frac{d}{dt} T_{n+1}^{(2,1)} - T_n^{(2,1)} \]

For the inner point at (2,2):

\[
\frac{1}{\alpha_{Al}} \frac{d}{dt} T_{n+1}^{(2,2)} - T_n^{(2,2)} \]

For the boundary point at (2,1):

For conventional FDM or FVM based solution, some numerical iteration method should be introduced to solve the massive equation set. Sometimes, it is found to be implicit to the final numerical results. In this study, the discrete equation sets are transformed into state space matrix form of \( A T^{n+1} = B + (1/A_{Al} \times dt) T^n \) where \( A \) and \( B \) are coefficient matrix; \( T \) is the vector of sequence of unknown temperature at point of \((1,1), (2,1), ..., (n_e, n_r)\); and \( n \) represent time node.

After careful arrangement, the explicit expression of matrix \( A \) is shown by Eq. (12). It should be noted that this is a block matrix and the \( A_1, A_2, A_3 \) and \( A_4 \) are given by Eq. (13–16).

For the boundary point at (2,1):

For the inner point at (2,2):

For the boundary point at (2,1):

For the inner point at (2,2):

For the boundary point at (2,1):

For the inner point at (2,2):

For the boundary point at (2,1):

For the inner point at (2,2):
The coefficient $C_1$ and $C_2$ in Eq.(13) and Eq.(14) can be calculated by Eqs.(17) and (18).

$$C_1 = \frac{1}{\alpha_{Ad} dt} + \frac{2}{d^2 x} + \frac{2}{d^2 y} + \frac{h_c + h_r + h_b}{\lambda_{Ad} dz}$$  \hspace{1cm} (17)

$$C_2 = \frac{1}{\alpha_{Ad} dt} + \frac{2}{d^2 x} + \frac{2}{d^2 y} + \frac{h_c + h_r}{\lambda_{Ad} dz}$$  \hspace{1cm} (18)

Moreover, the coefficient vector $B$ is expressed by Eq.(19). And vector $T$ is given by Eq.(20).

$$B = \begin{bmatrix} a T_c + k (T_h - T_c) - \frac{1}{R_c} T_1 \\ \frac{1}{R_c} T_h \\ \frac{1}{R_h} T_1 \\ \frac{1}{R_h} T_h \\ \frac{1}{R_f} T_1 \\ \frac{1}{R_f} T_h \\ \frac{1}{R_f} T_1 \\ \frac{1}{R_f} T_h \end{bmatrix}$$  \hspace{1cm} (19)

$$T = \begin{bmatrix} T_{1(1,1)}, T_{1(1,2)}, \ldots, T_{1(nx,1)}, T_{1(2,1)}, T_{1(2,2)}, \ldots, T_{1(nx,ny)} \end{bmatrix}^T$$  \hspace{1cm} (20)

By implementing the inverse of matrix $A$, the temperature field at time node $(n+1)$ can be easily calculated by Eq.(21). By using the explicit Eq.(21), the dynamic temperature field can be accurately simulation with fast speed. Moreover, this way of modeling makes it very flexible, which facilitate the model modifications and improvements.

$$T^{n+1} = A^{-1} \left( B + \frac{1}{\alpha_{Ad} dt} T^n \right)$$  \hspace{1cm} (21)

In order to make sure the successful running of this model, another equation should be supplemented to bridge the relation between surface temperature near TEM at $T_1$ and the heat flux from TEM $Q_c$. As Fig. 3 illustrated, the thermal energy transfer among $T_b$, $T_c$ and $T_h$ can be simplified as one-dimensional heat transfer. The equations are given by Eq.22 and 23.

$$a IT_c - k (T_h - T_c) - \frac{1}{R_c} T_1 = \frac{T_1 - T_c}{R_c}$$  \hspace{1cm} (22)

$$a IT_h - k (T_h - T_c) + \frac{1}{R_h} T_1 = \frac{T_1 - T_f}{R_h}$$  \hspace{1cm} (23)

By implementing matrix transform, the solution of Eqs. (22) and (23) can be given by $T_{ch} = [T_c, T_h]^T = A_5^{-1} A_6$, where $A_5$ and $A_6$ are given by Eqs. (24) and (25).

$$A_5 = \begin{bmatrix} a I + k + \frac{1}{R_c} \\ \frac{1}{R_h} \end{bmatrix}$$  \hspace{1cm} (24)

$$A_6 = \begin{bmatrix} \frac{1}{2} T_1 + \frac{1}{R_c} T_1 \\ \frac{1}{R_h} T_f \\ \frac{1}{R_h} T_1 \\ \frac{1}{R_h} T_h \\ \frac{1}{R_f} T_1 \\ \frac{1}{R_f} T_h \\ \frac{1}{R_f} T_1 \\ \frac{1}{R_f} T_h \end{bmatrix}$$  \hspace{1cm} (25)

2.3. Steady state modeling

When the steady state simulation is required, the model can be easily built based on the format of dynamic state modeling content.
The time-related terms, for example, in Eqs. 8–11 could be removed. And there is no need for marks of time node at super-script of each variable. Then, similarly, the discrete equation sets are transformed into state space matrix form of $CT = D$ where $C$ and $D$ are coefficient matrix; $T$ is the vector of sequence of unknown temperature at point of $(1,1)$, $(2,1)$, ... $(h_x, h_y)$. Based on comparison, it is found that the format of $C$ and $A$ is identical and the $D = B$. The only changes are the coefficient $C_1$ and $C_2$ in Eq.(13) and Eq.(14). In order to make a distinction, for the matrix, $C_3$ and $C_4$ are used and given by Eq.(26) and Eq.(27).

$$C_3 = \frac{d^2}{dx^2} + \frac{1}{\lambda A} {h_c + h_r + h_b}$$

$$C_4 = \frac{d^2}{dy^2} + \frac{1}{\lambda A} {h_c + h_r}$$

By implement the inverse of matrix $C$, the temperature field under steady state can be easily calculated by $T = C^{-1}D$. By using the explicit solution, the surface temperature field can be accurately simulation with fast speed.

2.4. ANN model for TRT

In this study, the dynamic thermal response of TERP is concerned. According to the thermal response time (TRT) study on conventional hydronic radiant panel system [31], it is originally defined as "the time for the system to change from one stable condition to another." Ning et al. [31] proposed to use the term "response time (95\%)" with the definition: "The time it takes for the surface temperature of a radiant system to reach 95% of the difference between its final and initial values when a step change of input is applied". Within this study, an improved and revised conception of TRT will be proposed based on in-depth analysis on the dynamic thermal characteristics of TERP, which will be discussed in Section 4. Based on this detailed mechanism analysis, a practical model for predicting TRT of TERP is to be built. Considering the intrinsic connection among indoor air temperature, initial surface temperature of radiant panel, different thermal condition in air duct, working current of TEM, as well as the sizing and shape of typical region concerning different arrangement of TEMs, an artificial neural network model (ANN) presented in Fig. 4 is adopted.

There are basically two reasons to adopt ANN for TRT. (1) According to the definition of TRT, in order to obtain the TRT value, one should finish calculating the entire temperature variation curve to the steady state. Although by using the newly proposed matrix-based model, both accuracy and simulation speed can be ensured, it is still not convenient if different designs of TERP are compared and evaluated. But by using ANN model, as Fig. 4 denotes, the entire process can be greatly simplified. (2) If an optimal on-line control of TERP system is requested, the calculation method based on heat transfer simulation can hardly compete with ANN. In this study, the ANN is trained by data collected from a large amount of simulations. But if the condition is allowed, the ANN model for TRT could be further improved by using a huge set of experimental data which may involve some noise signals that the heat transfer model cannot account.

As for the network structure, a forward neural network (FNN) is chosen. The six parameters in input layer and the one result in output layer is determined. In this modeling, considering the research complexity, the maximum neurons number is limited up to 1000, the number of hidden layers is limited to 4 layers and the choice of activation includes Logistic-Sigmoid and ReLU function. As Fig. 5 shows, when constructing the network, in each hidden layer, a linear layer and activation function layer is placed. Considering the behavior of TRT with different system parameters and different combination of system parameters, there are altogether 500 set of data is prepared and 80% of data are randomly picked as training set and the rest 20% of data becomes testing dataset. The training and testing data are from numerical simulations. The supervised learning is adopted for ANN training and Stochastic Gradient Descent (SGD) [38] is adopted for the problem optimization. In addition, it is noted that over-fitting issue is considered in this model. The over-fitting is usually occurred if some unnecessary information (noise) is learned by ANN which lead ANN to a wrong direction. In this study, the k-fold cross-validation method (Fig. 5) is adopted to avoid over-fitting, where the value of k is 10 in this study.

3. Model verification

3.1. Experiment setup and uncertainties

An experimental rig was built in a man-made environment chamber according to the Fig. 1. The main component of radiant panel, insulation material and heat sink are assembled as Fig. 6 shown. Besides a testing system was employed for dynamically measuring the surface temperature of radiant panel as well as indoor/outdoor thermal environment. The key specifications for the experimental instrument are listed in Table 1. The main uncertainty in experiment is the error of thermocouples due to its own manufacture error, which is listed Table 1.

The surface temperature of TERP is not uniform. Therefore, $T_1$, $T_2$, $T_3$ (on Fig. 1) are measured for the target temperature showing the performance of TERP. Meanwhile, the cold and hot side temperature of TEM is also measured and recorded for model validation. It should be noted that the location of $T_1$ is at the center position, $T_3$ at the edge position and $T_2$ in between.

3.2. Comparison results and analysis

A series of experimental measurement was conducted to verify the proposed new model. In the dynamic state condition experiment, the indoor air temperature was set around 24 °C but there was some fluctuation because it is controlled by split air conditioner. The air temperature in the air duct was also ventilated by the air flow from outdoor environment and pushed by DC fans to remove extra heat. Therefore, the input data were measured in experiment and then used in model. The working voltage was set as constant 4V in experiments. The rest parameters for simulations can be found in Table 2.

It should be noted that the uncertainty of temperature sensors simply influences the accuracy of indoor and outdoor air
temperature measurements. This results in some uncertainties in the final output simulations. Therefore, in the following simulation results, as well as the input data, are expressed with error range for showing their uncertainty. Fig. 7 shows the comparison results of temperatures of TERP in experiment and simulation under working voltage of 4 V. Mean Relative Error (MRE) is adopted to quantify the simulation error. Fig. 7(a) presented the input data. The noise of indoor air temperature containing fluctuation has been removed and the processed data are used in model. But the uncertainty of the input data is shown by error bar with 0.3 °C which comes from both the data logger and the temperature sensors. Meanwhile, all the simulation and measurements are expressed with error bars, in which the uncertainty of experimental measurements is 0.3 °C and by adjusting input data with variation within 0.3 °C, the simulation of T1, T2, T3, Tc, Th are showing different uncertainties. In general, their uncertainties are about 0.27–0.31 °C.

Fig. 7(b) and (c) compared the results of cold and hot side temperature of TEM. It is shown that the proposed model can accurately follow the curve of experiment with minor error. The mean relative errors for Tc and Th are respectively 2.76% and 1.56% and the major error may come from the estimation of thermal resistance value in the model.

In addition, as Fig. 2 indicated that three temperature sensors on the typical region of TERP were placed for recording the dynamic and non-uniform surface temperature. Fig. 7(d), (e) and (f) presented the comparison results of T1, T2 and T3. Those results clearly indicate the simulated surface temperatures are in good agreement with experiment data with both tendency and accuracy. The curves fluctuation is due to the unstable indoor air temperature. Besides, it is observed that surface temperature of TERP can be gradually cooled down within only 20 min which is much faster than conventional radiant panel system. The results also show that the averaged relative errors for T1, T2 and T3 are respectively 0.73%, 4.5% and 4.7%. The comparison basically demonstrated the effectiveness of the proposed model.

### 4. Analysis and discussions

In this section, a deep discussion will be delivered to the TRT asynchronism phenomenon, impact of step change of parameters, relationship between TRT asynchronism and surface temperature non-uniformity. New concepts of TRT will be put forward for TERP. Besides, the results of the proposed ANN-based model for TRT predicting will be presented which may offer a valuable tool for system dynamic intelligent control. It should be noted that for the following analysis, the default values for the TERP system are: Tm = 24 °C, Tl = 35 °C, I = 1.5A, To = 28 °C, Lx = 0.5 m, fshape = 1.0 = Lx/La, dt = 1.0s, the material of radiant panel is aluminum. Those default values of the system are obtained from the experimental test in model verification section. Only the size parameters are renewed with a more standard layout.

#### 4.1. TRT and its asynchronism

It is clear that when TEM starts working, the entire panel surface will be cooled down. But it is not clear if each point on the panel is in the same pace. More precisely, it is unknown if each point has the same TRT value under a certain condition. The existence of TRT asynchronism is investigated under two basic settings: one is when the initial surface temperature is higher than indoor air temperature, namely case 1: T0 > Tm and another is case 2: T0 < Tm.

### Table 1

| Experimental instruments                  | Manufacturer and model                                      | Key technical data                                      | Measurement error/uncertainty |
|------------------------------------------|------------------------------------------------------------|----------------------------------------------------------|-------------------------------|
| Data logger                              | Agilent Keysight Technology Cooperation (34972A LXI Data Acquisition/Switch) | The plug-in module: (1) scanning speed: 60 channel/s; (2) maximum input: 300V, 1A, 50W. | The minimum resolution: 1 μV, 0.1 °C |
| Thermocouples                            | PT 100 RTD thermocouples                                   | Temperature range: -50 to 200 °C; Input: AC 220V; Output: 0–30V/0–6A. | Uncertainty: 0.2 °C |
| DC power source                          | UTP1306S                                                  |                                                          |                               |

### Table 2

| Model parameters of TERP. | Values |
|---------------------------|--------|
| Seebest coefficient, α    | 0.05 V/K |
| Thermal conductivity of TEM, k | 0.55 W/K |
| Electric resistance of TEM, R | 2.23 Ω |
| Thermal conductivity of aluminum panel, λ | 230 W/mK |
| Thermal diffusivity of aluminum panel, a | 0.574 × 10⁻⁵ m²/s |
| Thickness of aluminum panel, dz | 0.002 m |
| Thermal resistance at cold side, Rc | 0.05 K/W |
| Thermal resistance at hot side, Rh | 0.3 K/W |
| Thickness of insulation board, do | 0.04 m |
| Thermal conductivity of insulation, λb | 0.02 W/mK |
| Time step in simulation, dt | 60 s    |
The results for the case 1 are presented in Fig. 8(a). According to the conventional TRT definition, the threshold value of 95% is set. In order to better showcase the evolution of surface temperature, five observation points (T1 to T5) are set on the surface of TERP. Different TRT threshold values are tested and compared which can better reflect the temperature evolution. It is shown for TRT95 is ascending from T1 (source point) to T5 (edge point). Although those point are cooled, but they are indeed not in the same pace. The TRT95 of T1 and T5 are 25 min and 31 min respectively. There is a 6 min difference. This shows the existence of TRT asynchronism for TERP. To facilitate the further investigation, we defined this value difference as Asynchronism Magnitude: $AM = TRT95(T5) - TRT95(T1)$. This newly defined concept can partially reflect the degree of asynchronism.

A further analysis is given by Fig. 8(b), in which the impact of working current and indoor air temperature on the value of AM is presented. Despite of indoor air temperature, the higher working current leads to larger AM value, because under this condition, more cooling energy is to be delivered from T1 to T5, which consumes longer time for the edge to reach steady state. In addition, it
Fig. 8. Surface temperature asynchronism under different TRT threshold settings when the initial surface temperature is higher than indoor air temperature.

Fig. 9. Surface temperature asynchronism under different TRT threshold settings when the initial surface temperature is lower than indoor air temperature.

Fig. 10. AM value distribution under various indoor air temperature and initial panel surface temperature settings.

Fig. 11. AM value distribution under various sizing and shape parameter settings.
that when the trend is growing in absolute value. Another difference from case 1 is that the source otherwise costs more time to reach steady state, and this is shown by a negative value of AM which means the point at heat for the situation when current is very low, the rest results are all shown here. As for the discussion on AM in Fig. 9(b), it is found that except that of T5 by 1.6 min. But the TRT asynchronism is still observed more time than the T5. Therefore, the TRT95 of T1 is longer than that of T5 by 1.6 min. But the TRT asynchronism is still observed here. As for the discussion on AM in Fig. 9(b), it is found that except for the situation when current is very low, the rest results are all showing a negative value of AM which means the point at heat source otherwise cost more time to reach steady state, and this trend is growing in absolute value. Another difference from case 1 is that when \( T_{in} \) is smaller, the absolute value of AM becomes larger.

Although the above case study demonstrated the existence of TRT asynchronism, the indoor air and the initial surface temperature and their combination seems to have an important impact on AM. Therefore, a further study result is presented in Fig. 10. It is clear that in the left upper area AM keeps positive while in the right lower area all the AM keeps negative. This is in accordance with case 1 and case 2 mentioned before. When the panel initial temperature is larger than indoor temperature, AM is positive, and vice versa. And if difference between \( T_{in} \) and \( T_{0} \) is larger, the value of AM becomes smaller. In addition, if the cross-section of the contour is compared, for example in the horizontal cross section, the \( T_{in}-\text{AM} \) curves under different \( T_{in} \) settings are nearly translational to each other. The same phenomenon is also observed for the vertical cross section for the \( T_{in}-\text{AM} \) curves under different \( T_{in} \) settings.

It is assumed that the sizing and shape of the typical region also has an impact on AM distribution. This issue is investigated by Fig. 11. The result clearly shows that the AM value is strongly linked to sizing of typical region \( Lx \) while weakly linked to the shape of the region. With longer region, the AM value increase with slower speed, according to the horizontal cross section curves.

Considering the material of radiant panel may insert some impact on AM value of TERP, ten different mental materials (Table 3) are selected for comparison. Under the default system settings, the results with different panel material are presented in Fig. 12, arranged based on the value of its thermal conductivity. It should be added that if the thermal diffusivity is used for dependent variable, the curves keep the same. The results indicate that the material with better performance of thermal conduction can help with shortening AM value and hinders the TRT asynchronism effectively. This meets with our expectations but what new value added here is that the curve becomes flat when \( \lambda \) is larger than 150 W/(mK). The mental with higher thermal conductivity usually are more costly. These results may help with panel material selection.

### 4.2. Step change of parameters

As mentioned in the conventional definition of TRT [31] that “The time it takes for the surface temperature of a radiant system to reach 95% of the difference between its final and initial values when a step change of input is applied”, only one single step change of input is concerned. This will neglect the dynamic response of radiant system when a second step change is imposed. In this sub-section, a two-stage step change of working current (control variable) and the indoor air temperature (environmental variable) is investigated and discussed with new observations.

First, the dynamic thermal response of TERP is studied when giving a step reducing change of working current from one stage to another. Within this discussion, two scenarios are considered: \( T_{0} > T_{in} \) and \( T_{0} < T_{in} \), because from the discussion in Section 4.1, the relation between panel initial temperature and indoor air temperature has obvious influence on the system response curve. Fig. 13 shows the results that in both two scenarios, when working current is reduced in the second stage, surface temperature will be warmer, despite of how temperature curves behave in the first stage. More importantly, it is seen that the TRT asynchronism becomes more obvious from the first stage to the second stage, with enlarged AM value.

Second, the dynamic thermal response of TERP is studied when giving a step increasing change of working current from one stage to another. The results are presented in Fig. 14. In both two scenarios, an increased step working current will result in cooler surface temperature, despite of how temperature curves behave in the first stage. And the phenomenon of an enlarged AM value is also observed in this case. More importantly, if Figs. 13 and 14 are vertically compared, a new finding is that, no matter it is step

### Table 3

| Number | Material    | Density | Thermal capacity | Thermal conductivity | Thermal diffusivity |
|--------|-------------|---------|------------------|----------------------|--------------------|
| 1      | Al          | 2710    | 902              | 236                  | 9.654E4-05         |
| 2      | 96Al–4Cu    | 2790    | 881              | 169                  | 6.8754E-05         |
| 3      | 92Al–8Mg    | 2610    | 904              | 107                  | 4.33497E-05        |
| 4      | 87Al–13Si   | 2660    | 871              | 162                  | 6.9922E-05         |
| 5      | Cu          | 8930    | 386              | 398                  | 0.000115463        |
| 6      | 90Cu–10Al   | 8360    | 420              | 56                   | 1.5949E-05         |
| 7      | 89Cu–11Sn   | 8800    | 343              | 24.8                 | 8.21267E-06        |
| 8      | 70Cu–30Zn   | 8440    | 377              | 109                  | 3.42565E-05        |
| 9      | 60Cu–40Ni   | 8920    | 410              | 22.2                 | 6.07022E-06        |
| 10     | Fe          | 7870    | 455              | 81.1                 | 2.26483E-05        |
increasing or decreasing change of current, the TRT for T1 to T5 keeps the same. This finding real that the dynamic response of TERP in a second stage in determined under a certain condition.

In order to further prove this judgement, an extended test is given to measure TRT at T1 and T5 under various pair of step change of current. A positive $\Delta I$ means a step increasing change and a negative means a decreasing step change. Table 4 clearly support the conclusion drawn from discussion on Figs. 13 and 14, under a certain environment, thermal response characteristics keep unchanged (AM becomes a constant) with different step change of current.

The conclusions from Table 4 naturally induce a discussion on impact of environmental change on dynamic response of TERP. It is practical because when the radiant system is functioned during a day, indoor environment condition may be unstable. It is assumed that in the first stage, indoor air temperature is 24 °C and in the second stage, it is either increased to 28 °C or decreased to 20 °C, while the current is kept as 1.5A. Fig. 15 shows the results that, although the tendency is different, the curves under 28 °C and 20 °C is mirrored to each other. More importantly, it is observed that the TRT asynchronism disappeared at the second stage because all the

| $\Delta I$ (A) | TRT1 | TRT5 | $\Delta I$ (A) | TRT1 | TRT5 |
|----------------|------|------|----------------|------|------|
| -1             | 15.7 | 29.43| 1              | 15.60| 29.38|
| -0.9           | 15.68| 29.45| 0.9            | 15.63| 29.4 |
| -0.8           | 15.67| 29.45| 0.8            | 15.65| 29.4 |
| -0.7           | 15.63| 29.45| 0.7            | 15.68| 29.4 |
| -0.6           | 15.62| 29.45| 0.6            | 15.70| 29.4 |
| -0.5           | 15.57| 29.45| 0.5            | 15.75| 29.4 |
| -0.4           | 15.52| 29.47| 0.4            | 15.80| 29.4 |
| -0.3           | 15.45| 29.47| 0.3            | 15.87| 29.4 |
| -0.2           | 15.32| 29.48| 0.2            | 15.98| 29.4 |
| -0.1           | 14.90| 29.52| 0.1            | 16.33| 29.33|
point reaches steady state at the same time.

4.3. Linking TRT and temperature distribution

Since the analysis of the first two subsections, the existence and basic features of TRT have been revealed. The TRT behaves its asynchronism in time scale. And it is also noticed that the surface temperature distribution of TERP behaves its non-uniformity in space scale. Here, we proposed a natural question: “are they linked with each other although those two characteristics belong to two different scales?”. If the answer is affirmative, then what kind of relation it should be?

A standard case of simulation is conducted based on default system parameter settings. Differ from analysis did in Section 4.1, the TRT value for each point in the typical region of TERP is calculated and arranged in matrix. Both the matrix of surface temperature and matrix of TRT values are displayed in their contour map in Fig. 16 for comparison. This initial comparison indicates that although those two maps are different in scale values, but nearly overlapped in distribution format.
In order to dig into the intrinsic link between surface temperature non-uniformity and TRT asynchronism, a series of additional investigations are implemented under various settings. The results are presented in Fig. 17. It is clear that no matter it is change of indoor air temperature \( T_{\text{in}} \) (Fig. 17(a)), air temperature in air duct \( T_f \) (Fig. 17(b)), or the working current of TEM \( I_{\text{item}} \) (Fig. 17(d)), the panel surface temperature and its corresponding TRT values are highly correlated, with 0.99 \( R^2 \) value from statistically aspect. However, there are also some complex factors inside this correlation as Fig. 17(c) showed that a highly non-linear relationship. From previous gained knowledge about TRT of TERP, this is caused by the setting \( T_0<T_{\text{in}} \) which leads to non-monotonous variation of the temperature curves. Therefore, a safe conclusion can only be given when the \( T_0>T_{\text{in}} \) situation is involved.

4.4. Re-defining TRT

From the conclusion of last subsection, if there is surface temperature non-uniformity, the TRT asynchronism is definite. Considering that the original TRT definition [31] did not involve this issue, a new definition of TRT for TERP or even for the other kind of radiant panel system with TRT asynchronism should be proposed. There are three candidate definitions of TRT named as TRT1, TRT2 and TRT3:

- TRT1 means “the largest TRT value in the TRT matrix for entire typical region”.
- TRT2 means “the averaged value of TRT matrix”.
- TRT3 abandon to measure TRT from surface temperature evolution but from angle of the evolution of cooling capacity. It is defined as “The time it takes for the cooling capacity of a radiant system to reach 95% of the difference between its final and initial values when a step change of input is applied”.

A series of test is conducted to show the difference among three definitions of TRT. As Fig. 18(a) indicated, under a certain setting of indoor air temperature, the difference between TRT1 and TRT2 is enlarging and under a certain working current, the higher indoor temperature also results in the higher difference. The definition of TRT1 is safest but it may not suitable for practical application because it ignores the situation of other points on the panel. But Fig. 18(b) suggests that TRT2 and TRT3 are quite similar, which can support that by doing averaging TRT it can also reflect the evolution of cooling capacity of the radiant panel. Considering the temperature measurement is easier than cooling capacity, in the following analysis, the definition TRT2 is adopted.
Table 7
Response table of system TRT.

| S/N ratio 2 | Level | Tin | T0 | Item | Lx | rshape |
|-------------|-------|-----|----|------|----|--------|
| 850.16 | 1     | 776.07 | 847.54 | 810.05 | 838.99 | |
| 852.21 | 2     | 851.83 | 853.58 | 812.61 | 807.87 | |
| 810.64 | 3     | 849.68 | 811.20 | 867.74 | 818.34 | |
| 813.17 | 4     | 848.60 | 813.86 | 835.79 | 860.98 | |
| ∆(max-min) | 41.57 | 75.76 | 42.38 | 57.69 | 53.11 | |
| Contribution ratio (%) | 15.36 | 28.00 | 15.67 | 21.32 | 19.3 | |
| Impact order | 5     | 1     | 4     | 2     | 3     | |

4.5. Impact factors of TRT

The above discussions display the dynamic thermal characteristics of TERP from many aspects and dimensions. It is important to study the multiple impact factors for TRT. To better understand the impact degree, the order of impact, Taguchi method has been recommended as a robust method for the trial experiments design and fair analysis in addressing the multi-dimensional optimization problem [39].

Different from the original orthogonal experiment, Taguchi method considered the influence of some uncertainties in the analysis. The signal-to-noise (S/N) ratio is introduced as the objective function for the design of multi-variable experiments. In this study, the S/N ratio under the less-the-better objective is used as shown in Eq. (28). Because it is assumed that the less TRT indicates the better ratio under the-less-the-better objective is used as shown in signal-to-noise (S/N) ratio is introduced as the objective function considered in combinations, it may also appear the contrary setting. The working current of radiant panel inserts the highest impact, but the working current and environmental temperature has the least impact, comparing with other factors.

\[
\eta_{S/N} = -10 \log \left( \frac{1}{M} \sum_{i=1}^{M} \text{TRT}_i^2 \right) 
\]  

(28)

As Table 5 shows, five factors with four levels of each are prepared. The indoor air temperature is assumed within 22–25 °C for thermal comfort. The initial panel temperature is assumed to be a bit higher than indoor air temperature but due to different combinations, it may also appear the contrary setting. The working current of TEM is made within 1.5–3.0A. The size of typical region is controlled not longer than 0.5 m. The orthogonal array L16 (4^5) is selected.

Those 16 experimental tests are conducted and the results are listed in Table 6. Because in the “the-less-the-better” rule, the value of S/N ratio is negative. So, the value \( \eta^2 \) is adopted for indexing. The results in Table 6 is further re-arranged into Table 7 in which the value of max-min is calculated for each factor. Then the contribution ratio can be obtained. It is found that the initial temperature of radiant panel inserts the highest impact, but the working current and environmental temperature has the least impact, comparing with other factors.

4.6. Predicting TRT

Usually analytical methods are adopted to predict TRT in some engineering problems [40]. Based on the above analysis, the TRT seems unable to be predicted by analytic method. In this study, an artificial neural network model is introduced. Only two hidden layers are used and the maximum neuron number is 1000 for each layer. The optimization of the hyper-parameter of the number of neurons for each layer is difficult. We conducted massive searching for the best couple of neuron number for the first layer \( n_1 \) and the second layer \( n_2 \).

First, a massive training process is implemented for different settings of neuron numbers at two hidden layers and the RSME (root square mean error) for each setting is recorded and displayed in Fig. 19. It is found that the lowest error during model training is achieved when \( n_1 \) is 1000 and \( n_2 \) is 850. Since this neural network is determined, it is used to verify the testing set.

Second, the comparison between one testing data and nine ANN prediction data is shown in Fig. 20 through k-fold cross validation. The results show that over-fitting is avoided and the overall accuracy by ANN is satisfying. A further detailed calculating of simulation error by ANN is given in Table 8. It demonstrates that the ANN model can predict TRT of TERP under complex situation with acceptable error of RSME 1.95; MAPE 5.45%; SMAPE 5.02%. This means the proposed ANN model is practical.

Third, in terms of other details of ANN model, the model can calculate the TRT very fast, within about 2 s. The computer used for this ANN modeling and computation is a common PC, with the Intel (R) Core (TM) i5-6300HQ CPU @2.3 GHz and 8 G GB RAM.

5. Conclusion

In this study, a new model is proposed and a new angle of investigation on dynamic thermal characteristics of TERP is presented. An in-depth analysis is given to many different aspects of system dynamical features with some new observations. It is not only beneficial to TERP, but also can provide channels for other relevant studies. The main conclusions are drawn as follows:

(1) The proposed dynamic state model of TERP is a balanced model with good simulation accuracy, high calculation speed, and easy implementation. By comparing with experimental results, the mean relative errors for \( T_c \) and \( T_r \) are respectively 2.76% and 1.56%. The averaged relative errors for \( T_1, T_2 \) and \( T_3 \) are respectively 0.73%, 4.5% and 4.7%.

(2) The existence of TRT asynchronism for TERP is confirmed. A new concept of AM (Asynchronism Magnitude) is defined to measure the degree of TRT asynchronism. The value of AM is positive when panel initial temperature is higher than indoor temperature, but negative when it is lower than indoor temperature. The AM value is strongly linked to the size of the typical region while weakly linked to the shape of the region. The panel material with higher thermal conductivity
can help with shortening AM value and restrain the TRT asynchronism effectively. But this effect is weakened when the thermal conductivity of material is larger than 150 W/(mK).

(3) When a two-stage current is imposed, the TRT asynchronism becomes more obvious from the first stage to the second stage, with enlarged AM value. A new finding is that, under a certain environment, thermal response characteristics remain unchanged (AM becomes a constant) even when different step changes of current are imposed. More importantly, when the environmental condition (such as indoor air temperature) is step changed, it is observed that the TRT asynchronism disappeared at the second stage because all the point reaches steady state at the same time.

(4) The correlation between surface temperature distribution and the TRT value distribution of TERP is studied for the first time. It is concluded that when the evolution curve of surface temperature is monotonous, the distribution of surface temperature and TRT is highly overlapped.

(5) Three new definitions of TRT is proposed and discussed. The second definition using averaged TRT matrix of the radiant panel meets with practical value. Based on this definition, multiple-factor impact on TRT is analyzed by using Taguchi method with signal-to-noise ratio evaluation. In the end, an ANN model is adopted to predict TRT value under complex parameter settings. The results suggest that the model...
prediction accuracy could reach RSME 1.95; MAPE 4.5%; SMAPE 5.02%.

If the TERP system is employed for spacing air conditioning in buildings, the unsteady outdoor thermal conditions and variation of indoor thermal demand, will force this TERP operating under a dynamic state. In order to better regulate indoor thermal environment and thus control TERP, the dynamic characteristics of TERP must be mastered, monitored, and understood. This study in the end provided a robust model for simulating system performance. When a certain demand is requested and this model can react quickly and make the best adjustment and control. This can lay down a foundation for a better design, control, and optimization of the system, towards a more energy efficient building.

Authorship Contribution Statement

Yongqiang Luo: Conceptualization, Methodology, Simulation, Writing - original draft, Funding acquisition. Tian Yan: Writing - original draft, Software, Validation, Writing - review & editing. Nan Zhang: Software, Writing - review & editing.

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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References

[1] Li Q, Guan X, Wu P, Wang X, Zhou L, Tong Y, et al. Early transmission dynamics in wuhan, China, of novel coronavirus--infected pneumonia. The New England of Medicine 2020. https://doi.org/10.1056/NEJMoa2001316.
[2] Lu R, Zhao X, Li J, Niu P, Yang B, Wu H, et al. Genomic characterisation and epidemiology of 2019 novel coronavirus: implications for virus origins and receptor binding. Lancet 2020;395:565–74.
[3] Joe J, Karava P. A model predictive control strategy to optimize the performance of radiant floor heating and cooling systems in office buildings. Appl Energy 2019:245–72.
[4] Labat M, Lorente S, Mosa M. Influence of the arrangement of multiple radiant ceiling panels on the radiant temperature field. Int J Therm Sci 2020:106184.
[5] Pfytasra MT, Bellos E, Tzivanidis C, Antonopoulos KA. Numerical simulation of a solar cooling system with and without phase change materials in radiant walls of a building. Energy Convers Manag 2019;188:40–53.
[6] Ramaa A, Anoma M, Zhu L, Rephael E, Fan S. Passive radiative cooling below ambient air temperature under direct sunlight. Nature 2014:515:540–4.
[7] Zhai Y, Ma Y, David SN, Zhao D, Lou R, Tan G. Scalable-manufactured randomized glass-polymer hybrid metamaterial for daytime radiative cooling. Science 2017:355:1062–6.
[8] Mandal J, Fu Y, Overvig AC, Jia M, Sun K, Shi NN, et al. Hierarchically porous polymer coatings for highly efficient passive daytime radiative cooling. Science 2018:351.3:315–9.
[9] Teitelbaum E, Chen KW, Meggers F, Pantelcic J, Aviv D, RysaneK A, The Cold Tube: membrane assisted radiant cooling for condensation-free outdoor comfort in the tropics. J Phys Conf 2019:1343:012080.
[10] Teitelbaum E, Rysanek A, Pantelcic J, Aviv D, Obelz S, Buff A, et al. Revisiting radiant cooling: condensation-free heat rejection using infrared-transparent enclosures of chilled panels. Architect Sci Rev 2019:62:152–9.
[11] Aili A, Zhao D, Lu J, Zhai Y, Yin X, Tan G, et al. A kW-scale, 24-hour continuously operational, radiative sky cooling system: experimental demonstration and predictive modeling. Energy Convers Manag 2019:186:586–96.
[12] Lertsatthithanakorn C, Srisuwan W, Athattajirayakul S. Experimental performance of a thermoelectric ceiling cooling panel. Int J Energy Res 2008:32;950–7.
[13] Liu Z, Zhang L, Gong G. Experimental evaluation of a solar thermoelectric cooled ceiling combined with displacement ventilation system. Energy ConverS Manag 2014:87:559–65.
[14] Liu ZB, Zhang L, Gong GC, Han TH. Experimental evaluation of an active solar thermoelectric radiant wall system. Energy ConverS Manag 2015:94:253–60.
[15] Liu Y, Zhang L, Liu Z, Wu J, Zhang Y, Wu Z. Three dimensional temperature field of thermoelectric radiant panel system: analytical modeling and experimental validation. Int J Heat Mass Tran 2017:114:169–86.
[16] Luo YQ, Zhang L, Liu ZB, Wang YZ, Meng FF, Xie L. Modeling of the surface temperature field of a thermoelectric radiant ceiling panel system. Appl Environ 2016:162:675–86.
[17] Lertsatthithanakorn C, Wiset L, Athattajirayakul S. Evaluation of the thermal comfort of a thermoelectric ceiling cooling panel (TE-CCP) system. J Electron Mater 2005:38:1472–7.
[18] Shen LM, Xiao F, Chen HK. Xiang SW. Investigation of a novel thermoelectric radiant air-conditioning system. Energy Build 2013:59:123–32.
[19] Lim H, Jeong J-W. Applicability and energy saving potential of thermoelectric radiant panels in high-speed train cabins. Int J Refrig 2015:104:229–45.
[20] Lim H, Jeong J-W. Energy saving potential of thermoelectric modules integrated into liquid desiccant system for solution heating and cooling. Appl Therm Eng 2018:136:69–72.
[21] Pourkiaei SM, Ahmadi MH, Sadeghzadeh M, Moosavi S, Pourfayaz F, Chen L, et al. Thermoelectric cooler and thermoelectric generator devices: a review of present and potential applications, modeling and materials. Energy 2019:186:115849.
[22] Weera S, Lee H, Attar A. Utilizing effective material properties to validate the performance of thermoelectric cooler and generator modules. Energy ConverS Manag 2020:205:112427.
[23] Lim H, Kang Y-K, Jeong J-W. Thermoelectric radiant cooling panel design: numerical simulation and experimental validation. Appl Therm Eng 2018:144:248–61.
[24] Shen L, Tu Z, Hu Q, Tao C, Chen H. The optimization design and parametric study of thermoelectric radiant cooling and heating panel. Appl Therm Eng 2017:112:688–97.
[25] Jin W, Ma J, Jia L, Wang Z. Dynamic variation of surface temperatures on the radiant ceiling cooling panel based on the different supply water temperature adjustments. Sustainable Cities and Society 2020:52:101805.
[26] Sun H, Lin B, Lin Z, Zhu Y, Li H, Wu X. Research on a radiant heating terminal integrated with a thermoelectric unit and flat heat pipe. Energy Build 2018;172:209–20.
[27] Sun H, Wu Y, Lin B, Duan M, Lin Z, Li H. Experimental investigation on the thermal performance of a novel radiant heating and cooling terminal integrated with a flat heat pipe. Energy Build 2020:208:109646.
[28] Du Y, Fell CJ, Duck B, Chen D, Liffman K, Zhang Y, et al. Evaluation of photovoltaic panel temperature in realistic scenarios. Energy ConverS Manag 2016:108:60–7.
[29] Hajaran R, Layeghi M, Sani KA. Experimental study of nanofluid effects on the thermal performance with response time of heat pipe. Energy ConverS Manag 2012:56:63–8.
[30] Guo Y, Wang J, Chen H, Li G, Li J, Xu C, et al. Machine learning-based thermal response time ahead energy demand prediction for building heating systems. Appl Energy 2018:221:16–27.
[31] Wong B, Schavon S, Bauman F. A novel classification scheme for design and control of radiant system based on thermal response time. Energy Build 2017:137:38–45.
[32] Wang Z, Hong T. Reinforcement learning for building controls: the opportunities and challenges. Energy Appl 2020:269:115036.
[33] Wang Z, Hong T, Piette MA. Building thermal load prediction through shallow machine learning and deep learning. Appl Energy 2020:263:114683.
[34] Dimri N, Tiwari A, Tiwari GN. An overall exergy analysis of glass-tedlar photovoltaic thermal air collector incorporating thermoelectric cooling: a comparative study using artificial neural networks. Energy ConverS Manag 2019:195:1350–8.
[35] Angeline AA, Asirvatham LG, Hemanth DJ, Jayakumar J, Wongwises S. Performance prediction of hybrid thermoelectric generator with high accuracy using artificial neural networks. Sustainable Energy Technologies and Assessments 2019:33:53–60.
[36] Acikgoz O, Cebi A, Dalkılıc AS, Koca A, Çetin G, Gemici Z, et al. A novel ANN-based approach to estimate heat transfer coefficients in radiant wall heating systems. Energy Build 2017:144:401–15.
[37] Fonseca N. Experimental analysis and modeling of hydronic radiant ceiling panels using transient-state analysis. Int J Refrig 2011:34:958–67.
[38] Nemurovska A, Juditsky A, Lan G, Shapiro A. Robust stochastic approximation approach to stochastic programming. SIAM J Optim 2009:19:1574–609.
[39] Taguchi C, Chowdhury S, Wu Y. Taguchi’s quality engineering handbook. Hoboken, NJ, USA: Wiley; 2004.
[40] Nemurovska A. Predicting response times of fixed-temperature, rate-of-rise, and rate-compensated heat detectors by utilizing thermal response time index. Fire Saf J 2006:41:516–27.
Nomenclature

\(a\): thermal diffusivity
\(A_{\text{TEM}}\): module area of TEM
\(C\): thermal capacitance
\(d_b\): thickness of insulation board
\(d_t\): time step
\(dx, dy\): space step in x-y direction
\(dz\): thickness of the radiant panel
\(h_b\): comprehensive heat transfer coefficient
\(h_c\): convective heat transfer coefficient
\(h_r\): radiative heat transfer coefficient
\(I\): working current
\(k\): thermal conductivity of TEM
\(L_x, L_y\): length of typical region
\(n_x, n_y\): node number in horizontal and vertical axis
\(q_c\): the heat flux density of TEM
\(Q_c, Q_h\): the cooling and heating capacity of TEM
\(R\): the electric resistance of TEM
\(R_c, R_h\): the cold and hot side thermal resistance
\(T\): surface temperature of panel
\(T_{\text{in}}\): indoor air temperature
\(T_f\): air temperature in the upper air duct
\(T_{\text{MRT}}\): indoor mean radiant temperature
\(T_c, T_h\): temperature at cool and hot side of TEM

Greek letters

\(\alpha\): Seebeck coefficient
\(\varepsilon\): panel surface emissivity
\(\rho\): density
\(\lambda\): thermal conductivity
\(\sigma\): the Stephen-Boltzmann constant

Abbreviations

AM: Asynchronism Magnitude
ANN: Artificial Neural Network
CV: Cross Validation
MAPE: Mean Absolute Percentage Error
MRE: Mean Relative Error
RSME: Root Square Mean Error
SMAPE: Symmetric Mean Absolute Percentage Error
TEM: Thermoelectric module
TERP: Thermoelectric radiant panel system
TRT: Thermal response time