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Dynamic heat transfer modeling and parametric study of thermoelectric radiant cooling and heating panel system

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ABSTRACT

Radiant panel system can optimize indoor thermal comfort with lower energy consumption. The thermoelectric radiant panel (TERP) system is a new and effective prototype of radiant system using thermoelectric module (TEM) instead of conventional water pipes, as heat source. The TERP can realize more stable and easier system control as well as lower initial and operative cost. In this study, an improved system dynamic model was established by combining analytical system model and artificial neural networks (ANN) as well as the dynamic calculation functions of internal parameters of TEM. The double integral was used for the calculation of surface average temperature of TERP. The ANN model and system model were in good agreement with experiment data in both cooling and heating mode. In order to optimize the system design structure, parametric study was conducted in terms of the thickness of aluminum panel and insulation, as well as the arrangement of TEMs on the surface of radiant panel. It was found through simulation results that the optimum thickness of aluminum panel and insulation are respectively around 1–2 mm and 40–50 mm. In addition, TEMs should be uniformly installed on the surface of radiant panel and each TEM should stand at the central position of a square-shaped typical region with length around 0.387–0.548 m.

1. Introduction

Buildings provide space for people to live and work in, while the air conditioning system guarantees its thermal comfort [1]. Basically, air system and radiant panel system are two major types of space cooling/heating system widely installed and used in both residential and public buildings. The radiant panel system is different from air system in various aspects. In terms of heat transfer process, the radiant panel system provides a combination of radiant and convective cooling to the room while air system cools the room by distributing cooled air into the entire indoor space through convective heat transfer [2]. Besides, radiant system handles the indoor sensible and latent loads separately while the control of air temperature and humidity in all-air system are coupled [3]. According to the above-mentioned differences, the radiant panel system can curtail approximately 40% of energy consumption compared with conventional Heating, Ventilation, and Air Conditioning (HVAC) systems [4,5]. The enhanced system efficiency comes from the higher temperature of supplied cooling water and reduced power consumed by fans. Although the energy efficiency on sensible heating and cooling by radiant system has been widely acknowledged, Kilkis [6] pointed out that this may not necessarily be true unless their low-exergy demand is matched with low-exergy waste and alternative energy resources.

Apart from energy conservation, a better indoor thermal comfort created by radiant panel system is another defining element that makes this system popular [7,8]. About 64–67% of heat transfer from radiant panel is contributed by radiation [9] and natural convection takes the rest, which can avoid cold draft and provide more uniform indoor air temperature distribution [10,11]. In addition, radiant system can save space and eliminate noise [8]. Yet any system has its inherent drawbacks and the conventional radiant panel system is no exception. The higher initial cost than all-air conditioning system hindered its further development in some developing or under-developed countries. What's more, the problem of panel surface condensation impeded its applications in hot and humid regions. The conventional method was to control the surface temperature of radiant panel higher than the dew point of indoor humid air, which inevitably lowered the system cooling capacity. Recently, lots of researchers aimed at the detection, control, prevention and eradication of surface condensation [12–16] through new designed structure or coupling with different ventilation system or dehumidification system.

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Nomenclature

Abbreviations

ANN	artificial neural networks
BIPVTE	building integrated photovoltaic thermoelectric
COP	coefficient of performance
Pr	Prandtl number
TEM	thermoelectric modules
TERP	thermoelectric radiant panel

Symbols

c	specific heat capacity of the aluminum panel (J/kg K)
h_c	front side convective heat transfer coefficients of TERP ($W/m^2{\cdot}K$)
h_b	back side over-all heat transfer coefficients of TERP ($W/m^2{\cdot}K$)
h_r	front side radiative heat transfer coefficients of TERP ($W/m^2{\cdot}K$)
Δh	time step (s)
I	operative current of TEM (A)
K	thermal conductivity of TEM ($W{\cdot}K^{-1}$)
m	number of virtual images of heat source
N	number of superposition of time
Q_c	the total heat flux transferred from the TE modules at the cold junction (W)
Q_h	the total heat flux transferred from the TE modules at the hot junction (W)
q_s	heat source intensity (W/m)
R_c	thermal resistance in the cold side of TERP (K/W)
R_h	thermal resistance in the hot side of TERP (K/W)
r_i	distance from the heat source i to any point on the surface of radiant panel (m)
R	electrical resistance of TEM (Ω)
T	temperature at any point on the surface of radiant panel (K)
T_c	temperature at cold side of TEM (K)
T_h	temperature at hot side of TEM (K)
T_f	temperature in the air duct (K)
T_{in}	indoor air temperature (K)
T_1, T_2, T_3	temperature at point 1, 2, 3 (K)
ΔT	temperature difference between any point on the surface of radiant panel and indoor air
v	air velocity in the air duct (m/s)

Greek symbols

α	seebeck coefficient ($V\,K^{-1}$)
β_{air}	coefficient of thermal expansion of indoor air (1/K)
δ	thickness of aluminum panel (m)
δ_b	thickness of insulation (m)
θ	surplus temperature (K)
λ	thermal conductivity of the aluminum panel and insulation (W/m·K)
λ_{air}	thermal conductivity of indoor air (W/m·K)
λ_b	thermal conductivity of insulation (W/m·K)
ν	kinematic viscosity (m^2/s)
ρ	density of aluminum panel (kg/m^3)
τ	time (s)
ω	coefficient in governing equation

Subscripts

b	insulation
c	cold
h	hot
in	indoor
f	air duct

Prototypes of radiant panel systems can be divided into many categories on the basis of their installation positions, panel materials, and heat sources. In terms of the installation positions of radiant panel, cooling or heating floor [16–19], ceiling [12,20–22], and wall [23–25] are three basic forms which received extensive attention. Generally, metal ceiling (aluminum panel usually) [26,27] and concrete floor or ceiling [3,28] are two conventional types which are featured with low and high thermal inertia respectively. As for the heat sources, cooling or heating water flow in the hydraulic pipes [12,28] or capillary [29,30] has been frequently employed in practice to cool or heat radiant panel.

Besides, another novel and effective radiant panel system using thermoelectric modules (TEM) as the heat sources was proposed [31–33]. The thermoelectric radiant panel system (TERP) has not only fully inherited the merits of conventional hydraulic radiant panel but also equipped with new characteristics brought by the introduced TEM, which can realize fast cooling/heating, a much easier system control and modes switch with direct electric current [34,35]. TEM is a small sized compact heat pump without working refrigerant, and the use of TEM can spare the refrigeration plant which is needed to provide cooling water for conventional radiant panel [36]. Previously, the experiments [31,32] and case study [33] about TERP were conducted which has proved its equivalent cooling capacity compared to conventional radiant panel system. In order to improve the thermal comfort and system performance, Liu et al. [37] incorporated the displacement ventilation with thermoelectric cooling ceiling and designed a PV module as the electric power provider in this complex system. Then, thermoelectric cooling and heating panel were vertically installed to fabricate a new kind of active building envelope which can largely cut heat gain in summer condition [24] and heat loss in winter condition [25]. Moreover, this active structure can cool or heat inner space in the daytime when the outdoor solar radiation intensity is enough to power the TEM.

The experimental investigations can deliver an approximate understanding about TERP system, but without mathematical models, the further studies can be hardly carried out. After deducing the new governing differential equation, Luo et al. [36] established an analytical heat transfer model which can accurately simulate the dynamic surface temperature of TERP system. This work laid down solid foundation for deeper analysis of TERP and provided a useful tool for the applications of TERP. For example, the analytical model of TERP was coupled with the math models of PV module, air duct and insulation board in the research by Luo et al. [23] to complete the complicated heat transfer analysis and system performance evaluation on a building integrated photovoltaic thermoelectric (BIPVTE) wall system. However, there are still some points about the dynamic model of TERP that should be addressed:

(1) The thermal resistance of heat pipe and the contact thermal resistance between TEM and aluminum panel should be dynamically calculated in the computation code instead of adopting the constant value set in the simulation in Ref [23,36], which is responsible for the calculation errors. But those two kinds of thermal resistances cannot be simply expressed in explicit functions so as to be coupled with the model of TERP.