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Modeling of the surface temperature field of a thermoelectric radiant ceiling panel system

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HIGHLIGHTS

- Thermoelectric radiant ceiling panel system (TE-RCP) is a novel and promising system.
- This paper delivered an analytical heat transfer model of TE-RCP.
- Heat source method and idea of virtual image as well as superposition principle and step load theory are adopted.
- A system coefficient of performance is proposed based on the steady state model of TE-RCP.

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ABSTRACT

Thermoelectric radiant ceiling panel system (TE-RCP) is a novel and promising system which combines the advantages of thermoelectric cooling/heating and conventional radiant ceiling panel system. The experimental investigations and case studies of TE-RCP have been carried out. But there is short of theoretical analysis and heat transfer model to provide a basis for the deeper and further investigation about TE-RCP. By solving the governing equation of the TE-RCP and using virtual heat source method to simulate the boundary conditions, the surface temperature field of TE-RCP under constant heat source intensity can be calculated. The dynamic-state model under variable heat source intensity is developed by adopting the idea of superposition principle and step load theory. The calculated temperature on the surface of radiant panel and hot/cold side of TE modules are in agreement with the experimental values. A system coefficient of performance (COP) is proposed based on the steady state model of TE-RCP to analyze the impact of working current of TE modules on the system performance. The simulations indicate that in cooling mode the system cooling capacity ranges between 48.6 W/m^2 and 104.1 W/m^2 and the corresponding system COP ranges between 1.06 and 2.29 under the working current from 1 A to 2 A. In heating mode, the system heating capacity ranges between 165.6 W/m^2 and 343 W/m^2 and the corresponding system COP ranges between 1.51 and 1.8 under the working current from 2 A to 3 A. This proposed model can provide a solid foundation for the further design, optimization, and system control of TE-RCP.

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1. Introduction

The thermal comfort in built environment is always one of the top concerns for human beings. The air conditioning system is the major channel to maintain the indoor thermal comfort but also a great contributor to building energy consumption. In general, the air conditioning terminals can be classified in two main categories: convective terminals and radiant terminals [1]. A lot of investigations have showcased the differences between the air system and radiant system [1–4]. By comparison the air system has all sorts of drawbacks such as risk of refrigerant leakage and indoor air contamination, uneven air temperature distribution and discomfort caused by cold drafts. Unlike the air system, the radiant system can remove space heat by means of both radiant and convective heat transfer, which is more challenging for cooling capacity estimation and system control. But radiant system can ensure indoor thermal comfort with higher energy efficiency as well as the better indoor air quality [1–3], which has attracted an increasing attention from researchers. Extensive studies have been conducted in terms of evaluating the thermal comfort and energy consumption of radiant ceiling system by using CFD and experiment method [5,6], system control [7], evaluating system cooling and heating

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Nomenclature

Abbreviations

COP	coefficient of performance
MPC	model predictive control
PDE	partial differential equation
Pr	Prandtl number
TEM	thermoelectric modules
TE-RCP	thermoelectric radiant ceiling panel

Symbols

a	thermal diffusivity coefficient (m^2/s)
c	specific heat capacity of the aluminum panel (J/kg K)
h_c	front side over-all heat transfer coefficients of TE-RCP (W/m^2 K)
h_b	back side over-all heat transfer coefficients of TE-RCP (W/m^2 K)
Δh	time step (s)
I	operative current of TEM (A)
K	thermal conductivity of TEM ($W K^{-1}$)
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 TE-RCP (K/W)
R_h	thermal resistance in the hot side of TE-RCP (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_{out}	outdoor 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	coefficient in Bessel function
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

performance [8–12], simplifying calculation method for estimating surface temperature and heat flux from radiant ceiling system [13–16], etc.

According to some literatures and data analysis, the radiant system is widely applied to European countries, North America, East Asia, and Southeast Asia [17] because of its advantages over the air system. But the shortcoming like water condensation on chilled ceiling surfaces will hinder its development in wider regions in the hot and humid areas. The resolution to this problem is to run the radiant system with other parallel systems for ventilations and to adopt a better control strategy. The systems like solar desiccant dehumidification system [18], radiant panel connected with airbox convector [19], and newly designed decentralized DOAS coupled with radiant cooling panels [20], can simultaneously satisfy the space sensible loads and ventilation requirements and largely reduce the risk of moisture condensation on the radiant cooling panels [17].

Because of the thermal mass of radiant heating/cooling system, advanced control strategies should be implemented to prevent it from overheating and condensation. Model predictive control (MPC) method is proven as an effective control strategy for radiant system [21] and the energy saving potential of MPC has been justified [22]. And lots of researches further developed the MPC like multi-structural fast nonlinear model predictive control (MPC) [23].

Apart from the problems of condensation and overheating, for the conventional hydronic radiant ceiling system, the cooling water is produced by refrigeration plants where the risk of refrigerant leakage remains [24]. Recently, a thermoelectric radiant ceiling panel (TE-RCP) system has emerged as another radiant system using thermoelectric modules (TEM) as heat source instead of conventional hydronic pipes [24–27]. Working as the heat source, TEM is a small sized heat pump characterized by the advantages of Freon free and rapid cooling/heating which can overcome the shortcomings of hydronic radiant ceiling system. Once the TEM is powered by direct current within proper range, it can absorb heat from indoor environment at cold side of TEM and transfer the heat by electron transport to the hot side of TEM [28]. The cooling and heating mode of TEM can be easily switched by changing the direction of current, and the system control is only related to the working current of TEM which simplified the system MPC. Moreover TEM can be powered by PV system which made solar thermoelectric air conditioner and many other innovative systems possible [29]. As for the cost, refrigeration plant is a million-dollar machine but TEM just takes less than 8 dollar per chip [30]. It is much cheaper for the installation and implementation of TE-RCP because it can be free from refrigeration plants, water pumps and other accessories. Detailed economic and system performance analysis has been carried out in the published reference [31] which has justified the feasibility of TE-RCP system. In general, the TE-RCP system has inherited most merits of hydronic radiant ceiling system while it can overcome some defects of the tradition one.

Shen et al. [24] presented a general analysis of TE-RCP system and a specific case study of TE-RCP on a virtual office space in

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