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Three dimensional temperature field of thermoelectric radiant panel system: Analytical modeling and experimental validation

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ABSTRACT

Thermoelectric radiant panel (TERP) system is a new prototype of radiant system with fast cooling/heating speed, stable operation, and easier system control. The full and deeper understanding of heat transfer of TERP could be beneficial for system design, operation and control. The purpose of this paper is to establish a three-dimensional analytical model of TERP in both steady and dynamic state which could be used as a useful tool for further research. The method of mirror virtual heat sources was adopted to transform original heat conduction problem to the superposition of temperature solutions of radiant panel in infinite plane. In addition, this method can offer a highly flexible treatment on boundary conditions. The basic conduction problem was solved by the method of separation of variables and the temperature field subjected to non-functional finite-plane heat source was modeled by Duhamel theorem in simulation algorithm. Thermal network RC model for TEM and copper cube was integrated with the analytical model of radiant panel for simulation of TERP. The simulation accuracy of three-dimensional temperature field of TERP was verified by comparing with experimental results in both steady and dynamic state. In order to understand the simulation difference between the previous 2-D and new 3-D model, a comparative study was implemented under different model parameters arrangements. This numerical comparative investigation can provide a basic guidance on the application of 2-D and 3-D model. And this study offered a solid and sophisticated system model for TERP.

1. Introduction

Air conditioning system is designed to control and adjust the indoor thermal environment to meet with users' demand for thermal comfort as well as indoor air quality. Considering different heat transfer process, all-air system and radiant system are two major categories of terminates used in building sectors. Compared to all-air systems which depend on convection only, the radiant system can provide cooling or heating by the combination of radiation and convection [1]. It is fairly acknowledged and confirmed by lots of researches that radiant systems are preferred over all-air systems because of their better ability to lower energy consumption [2–5] and maintain better comfort conditions [6–9]. The hydronic radiant panel system uses water pipes as the heat source to cool/heat indoor space surfaces and human skin directly instead of cooling or heating the entire indoor space like an all-air system. Therefore, the higher temperature of cool water and the lower temperature of hot water can be used in radiant system for space cooling/heating, which can largely reduce the working load of cooling/heating plant. In addition, radiant system can be free from cold draft, noise of operating fans and a large temperature gradient indoor [10,11].

Despite of the mentioned several advantages, radiant systems also encounter difficulties in system control for prevention of under-cooling or over-heating problems [12] and condensation on the panel surface [13]. For radiant system, cooling capacity is still supplied by refrigeration plant, the risk of refrigerant leakage remains [14,15]. Those natural defects of hydronic radiant panel systems (including radiant floor and ceiling systems) cannot be easily overcome through system design optimization. If new heat sources with characteristics of easier control, fast response and reasonable cost could be adopted and applied to radiant system, some aspects of shortcomings of hydronic radiant system can be handled. Thermoelectric module (TEM) [16,17] can be seen as a tiny, thin and compact solid heat pump with fast cooling/heating, easier control of heat flux, and being free from mechanical moving components, refrigerants [18], which has been the candidates for extensive applications like air heater [19], CPU cooler [20] or active envelope system [21], etc. Moreover, the cooling and heating mode of TEM can be easily switched by changing direction working current. Therefore it is possible to utilize TEM as a heat source for radi-

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Nomenclature

Abbreviations

AUST	area-weighted average temperature (K)
COP	coefficient of performance
ODE	ordinary differential equation
RC	resistance and capacitance
SOV	method of separation of variables
TEM	thermoelectric module
TERP	thermoelectric radiant panel

Symbols

a	thermal diffusivity coefficient (m^2/s)
c	specific heat capacity of the aluminum panel (J/kg K)
h_c	convective heat transfer coefficients of TERP (W/m^2 K)
h_r	radiative heat transfer coefficients of TERP (W/m^2 K)
h	time step (s)
I	operative current of TEM (A)
K	thermal conductivity of TEM ($W\,K^{-1}$)
m	number of eigenvalue
n	number of virtual images of heat source
Ns	number of superposition time
Q_c	cooling capacity of TEM (W)
q_s	heat source intensity (W/m^2)
R_{c1}	thermal resistance between copper cube and radiant panel (K/W)
R_{c2}	thermal resistance between copper cube and cold side of TEM (K/W)
R_h	thermal resistance between air in duct and hot side of TEM (K/W)
r_i	distance from the heat source i to calculation point on radiant panel (m)
r_s	radius of finite plane heat source (mm)
R	electrical resistance of TEM (Ω)
t	time (s)
T	temperature at any location of radiant panel (K)
T_c	temperature at cold side of TEM (K)
T_{cu}	temperature of copper cube (K)
T_h	temperature at hot side of TEM (K)
T_f	air 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)

Greek symbols

α	Seebeck coefficient ($V\,K^{-1}$)
β	variable in integral calculation
δ	thickness of aluminum panel (m)
θ	surplus temperature (K)
σ	Stefan-Boltzmann constant
ε	emissivity of surface of radiant panel
η_m	eigenvalue
λ	thermal conductivity of the aluminum panel (W/m K)
ρ	density of aluminum panel (kg/m^3)

ant cooling/heating rather than conventional water pipes, which is called as thermoelectric radiant panel system (TERP) [15].

To our knowledge and based on the search of the published literatures, relevant research on TERP system is insufficient and immature including both numerical simulations and experimental investigations. Lertsatitthanakorn et al. [22,23] firstly established an experimental setup for evaluating cooling capacity and thermal comfort under TERP system. There were 36 chips of TEM used for radiant panel installed in a test chamber of 4.5 m^3 volumes, while using circulating cooling water for heat dissipation of hot side of TEMs [22]. Shen et al. [14] independently proposed and analyzed the feasibility of using TEM as a heat source of radiant panel system. A case study was conducted by Shen et al. in terms of thermoelectric radiant system in Wuhan, China. Liu et al. made contributions for the further applications and possible system integration of TERP through a series of experiment investigations [24–26]. The total heat flux and COP of a thermoelectric radiant system integrated with displacement ventilation system was tested in an experimental chamber with dimension of 3 m × 3 m × 3 m [24]. The TEM is powered by direct current, which also makes the combination of photovoltaic system and TERP possible. The experimental evaluations on solar thermoelectric system in both summer conditions [25] and winter conditions [26] were reported.

As Kyu-Nam Rhee et al. mentioned in the discussion on 10 questions about radiant system [27], the heat transfer mechanism is the starting point of energy analysis of radiant cooling and heating. Similarly, the understanding of heat transfer in TERP system is critical for better design, optimization and system control. The TEMs used in TERP system are sparsely and uniformly distributed on the back surface of the radiant panel (such as aluminum panel). Unlike conventional hydronic radiant panel system, it is naturally a three-dimensional unsteady heat transfer problem for detailed modeling of TERP. In previously study of modeling work, Luo et al. formulated a specific governing equation for TERP system and solved a two-dimensional surface temperature field of TERP in analytical method of Laplace Transform [15]. And this analytical model was then integrated with an artificial neural network for better simulation accuracy in both cooling and heating mode [28]. Besides, this analytical model was proved to be valid when applied to the simulation of photovoltaic thermoelectric radiant wall system in which the working current and air temperatures were dynamically varied [29]. Although the thickness of radiant panel was considered in the previous study, the temperature gradient was neglected so as to simplify problem on two-dimensional heat transfer. The problems in previous model established by Luo et al. [15] are:

(1) the convective and radiative heat transfer between indoor space and radiant panel were integrated into the newly derived governing equation which inevitably may cause some problems in simulation;
(2) the modeling assumptions of 2-D model and simulation results indicated that the previous two-dimensional model can only be suitable for zero initial condition problem;
(3) the influence of panel thickness on temperature distribution cannot be directly analyzed;
(4) the model failed when $r = 0$ because in steady-state model the second type modified Bessel functions of zero order K_0(r) was used ($K_0(0)$ trends to be infinity and previously $K_0(r_s)$ was used for approximation estimation of temperature at $r = 0$).

Confronted with those limitations of the previous system model, it is necessary to develop a new analytical transient model in three-dimension to predict temperature field of TERP system, which can provide a more precise, robust and detailed simulation