Applied Thermal Engineering 144 (2018) 248–261

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Thermoelectric radiant cooling panel design: Numerical simulation and experimental validation

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HIGHLIGHTS

- A thermoelectric radiant cooling panel (TERCP) was proposed.
- Numerical simulation model for the TERCP was developed and validated.
- The simulation model was developed in graphical user interface.
- Desirable arrangement of thermoelectric modules (TEMs) on the TERCP was investigated.
- Triangular configuration with 0.28 m spacing between TEMs was selected.

ARTICLE INFO

Keywords:
Thermoelectric module
Radiant panel
Radiant air-conditioning
Temperature distribution
Designs process

ABSTRACT

The main objective of this research is to investigate desirable arrangement and spacing of thermoelectric modules (TEMs) to obtain uniform temperature distribution on the surface of a thermoelectric radiant cooling panel (TERCP). A TERCP numerical simulation model was developed based on a two-dimensional heat transfer analysis using the developed TEM model and the finite difference method. The graphical user interface (GUI) was also suggested to provide an easy-to-use design tool for TERCP. Using a developed simulation model, it was found that the triangular configuration of the TEMs on the top surface of the panel with 0.28 m spacing between the TEMs was the most suitable design choice that yields uniform temperature distribution on the bottom surface of the TERCP. To validate the simulation model and proposed panel design, an actual TERCP was constructed and tested under a controlled laboratory environment, and the temperature distribution on the panel surface was measured. The tested TERCP was made of aluminum panel with seven TEMs installed on the top side of the panel with copper substrate, and a heat sink was attached on the hot side of each TEM to release heat to air blowing through the heat sink. The design surface temperature of the proposed panel was 16 °C and the maximum temperature difference between the cold spot and hot spot on the panel surface did not exceed 3 °C as recommended by existing guideline. From the experimental validations, the panel temperature distributions predicted using the TERCP model were in good agreement with the measured panel temperature distributions with a mean error rate below 1.39%. In addition, the parametric study was conducted using validated numerical model to evaluate the effects of design factors and operation conditions on the cooling performance of the TERCP. The results showed that the spacing between TEMs, and outdoor air temperature for heat removal are the main factors to control the cooling performance of the TERCP.

1. Introduction

The ceiling radiant cooling panel (CRCP) has attracted increasing attention owing to its benefits of enhanced thermal comfort and energy conservation in building air conditioning [1–4]. The conventional CRCP is usually a hydraulic device receiving chilled water produced by the chiller based on the vapor compression refrigeration cycle. This system shows good energy efficiency and cooling performance; however, appropriate design, construction, maintenance, and control of hydraulic CRCP system in buildings are relatively difficult, and refrigerants used in chilled water plants still have negative impact on global environment [5–7].

As an alternative solution to the conventional hydraulic CRCP, a thermoelectric radiant cooling panel (TERCP) cooled by thermoelectric modules (TEMs) attached on the top side of the panel has recently been

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https://doi.org/10.1016/j.applthermaleng.2018.08.065
Received 4 June 2018; Received in revised form 2 August 2018; Accepted 18 August 2018
Available online 20 August 2018

Nomenclature

A	uniform cross-sectional area [m^2]
C_p	specific heat capacity [kJ/kg·K]
f_p	packing fraction of total TEM area covered by a thermo-element [–]
g	acceleration of gravity [m/s^2]
Gr	Grash of number [–]
h	heat convection coefficient [W/m^2·K]
I	current [A]
K	thermal conductivity of TEM [W/K]
l	height of the thermoelement [m]
L	length [m]
L_c	characteristic length [m]
n	number of TEMs [–]
N	number of thermocouples [–]
Nu	Nusselt number [–]
P	electrical power [W]
P_{duct}	perimeter of the plenum [m]
Pr	Prandtl number [–]
$\dot{Q}$	thermal energy [W]
R	electrical resistance of TEM [Ω]
Ra	Rayleigh number [–]
Re	Reynold number [–]
S	Seebeck coefficient of TEM [V/K]
T	temperature [°C]
th	thickness [m]
U	overall heat transfer coefficient [W/m^2·K]
v	velocity [m/s]
W	width [m]

Greek symbols

α	Seebeck coefficient for compact TEM [V/K]
β	coefficient of cubical expansion [°C^{-1}]
Δ	difference [–]
Δx	length of node in x-direction [m]
Δy	length of node in y-direction [m]
ε	effectiveness [–]
ε	emissivity [–]
κ	thermal conductivity of the compact TEM [W/(m·K)]
μ	viscosity [kg/(m·s)]
ρ	electrical resistivity of the compact TEM [Ω·m]
ρ	density [kg/m^3]
σ	Stefan-Boltzmann constant [W/(m^2·K^4)]

Subscript

a	air
act	actual
Al	aluminum panel
c	cold
con	conduction
conv	convection
Cu	copper
duct	duct or plenum
h	hot
hs	heat sink
i	node number in x-direction
in	inlet
ins	thermal insulation
j	node number in y-direction
max	maximum
MRT	mean radiant temperature
out	outlet
panel	panel
plenum	plenum
rad	radiation
room	room
surf	surface
TEM	thermoelectric module

Superscript

t	time [sec]

Abbreviations

COP	coefficient of performance
CRCP	ceiling radiant cooling panel
DOAS	dedicated outdoor air system
FDM	finite difference method
GUI	graphical user interface
TEM	thermoelectric module
TERCP	thermoelectric radiant cooling panel

proposed. The TEM is composed of n-type and p-type semi-conductor thermocouples and operated based on the Peltier effect, which delivers heat from a cold side to a hot side using the input electric power [8]. Therefore, TEM is commonly categorized as a solid state heat pump having advantages of compact size, no refrigerant, no moving part, no noise, and fast response [9]. In virtue of these advantages, many researches were being conducted continuously to find a way to use TEMs in the building air conditioning applications [10,11], such as a solar thermoelectric radiant wall [12] and a photovoltaic thermal-compound thermoelectric ventilator [13].

Lertsatitthanakorn et al. [14,15] constructed a water-cooled TERCP, and investigated its cooling performance and impact on thermal comfort in various operating conditions. The authors reported that the cooling performance of the system depends on the input current, as well as the temperature and flow rate of cooling water circulating through the hot side of the TEMs for heat rejection. Lim et al. [16] proposed the use of water-cooled TERCP in a zone served by a dedicated outdoor air system (DOAS) for ventilation. The authors carried out a detailed annual energy simulation, and reported that the water-cooled TERCP with DOAS could save 44.5% of annual operating energy compared to the conventional variable air volume system.

Shen et al. [17] suggested an air-cooled, non-hydraulic TERCP, which has benefits of convenient installation and no water distribution pipes. The researchers investigated the feasibility and performance of the proposed system using mathematical simulations and showed that the coefficient of performance (COP) of the air-cooled TERCP is comparable to that of the conventional air conditioning system. Liu et al. [18] also proposed an air-cooled TERCP powered by a photovoltaic system. Their TERCP was used in a conditioned zone with a displacement ventilation system, and yielded a COP of 0.9 for cooling and 1.9 for heating.

The above studies revealed the feasibility of air-cooled and water-cooled TERCP systems in building air conditioning; however, existing studies on optimal design of TERCP are still very limited. Shen et al. [19] proposed a one-dimensional analytical TERCP model for determining the optimal thickness of a radiant panel and the number of TEMs per unit panel area. However, the uniformity of temperature distribution on the radiant panel was not considered in determining the optimal spacing between TEMs, which is a critical issue in radiant panel design to prevent the condensation problems and improve its cooling capacity [20,21].