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Experimental investigation on the heat transfer coefficients of radiant heating systems: Wall, ceiling and wall-ceiling integration

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ABSTRACT

In recent years, radiant heating systems have been catching more observation under favor of the advantages in energy saving and thermal comfort. Radiant ceiling systems are preferred over radiant wall systems due to the easier application and less space constraint compared to wall systems. However in cold climates ceiling surface may not be enough to cover all heating loads. In this case radiant wall systems can be integrated to ceiling systems to cover the peak loads. In order to properly address calculation and design issues dealing with these systems, accurate estimation of the heat transfer phenomena is required for various types of applications. This paper evaluates the heat transfer characteristics of the hydronic heated radiant wall and ceiling systems, as well as their integrated configuration. A series of experiments were performed in which the main objective was to evaluate the heat transfer characteristics of the three different radiant panel arrangements. For this purpose, a climatic test chamber was built and values of total, radiant and convective HTCs were obtained and discussed. To calculate the heat transfer coefficients, tests were carried out using different supply water temperatures in the case of each arrangement. The HTCs were calculated by means of the characteristic temperatures. For the heated radiant wall, the approximate average values 8.57, 5.74 and 2.44 $W\,m^{-2}\,K^{-1}$ were obtained respectively for the total, radiant and convective HTCs. On the other hand, corresponding values for heated radiant ceiling cases are: 7.28, 5.70 and 0.82 $W\,m^{-2}\,K^{-1}$. Additionally for the radiant wall-ceiling integrated cases, HTC values were obtained for the wall and ceiling panels separately. When the wall is integrated to the ceiling, total and radiant HTCs decreased in both ceiling and wall, convective heat transfer coefficient also decreased in wall but increased in ceiling cases.

1. Introduction

Radiant heating and cooling systems have been preferred in place of conventional systems as an alternative with regard to their advantages on energy saving and thermal comfort. Besides, these systems can be operated with alternative energy sources (e.g. heat pumps and solar systems) that can generate low temperature water. Therefore, radiant heating and cooling systems can decrease energy consumption by using lower supply water temperatures for heating and higher supply temperature for cooling operations [1–9].

Radiant heating and cooling systems use indoor surfaces on the floor, walls, or ceiling at certain temperatures which is adjusted by circulating water through a hydraulic line embedded to the panel. A system called radiant system if more than 50% of heat exchange occurs from its surface through thermal radiation [10].

Heat transfer performance of the radiant systems is the most important design parameter during dimensioning processes of their engineering applications. Miriel et al. [6] studied thermal performances of radiant system for both cooling and heating operations. They reported that, 66% of the total heat transfer amount that took place at the cooled radiant ceiling was by convection, while it was 20% for heated radiant ceiling. Moreover, they proposed convective heat transfer coefficients (here after HTC) of 3.0 $W\,m^{-2}\,K^{-1}$ for cooled ceiling and 1.2 $W\,m^{-2}\,K^{-1}$ for heated ceiling. Okamoto et al. [11] proposed a simplified calculation model for evaluating thermal capacities of ceiling radiant panels. In their results, the fraction of radiant heat transfer amount to total heat transfer amount was 70–80% in heating and 60% in cooling. Jeong and Mumma [12,13] established a cooling performance estimation method for radiant ceiling panel and reported the impacts of several

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Nomenclature

A	Area (m^2)
c_p	Specific heat at constant pressure ($J\,kg^{-1}\,K^{-1}$)
$F_{\varepsilon_{s-j}}$	Radiation interchange factor
F_{s-j}	View factor between radiant surface and j-surface
h_{con}	Total heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
h_{rad}	Radiant heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
h_{tot}	Convective heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
$\dot{m}_w$	Water mass-flow rate ($kg\,m^{-3}$)
Q_{con}	Convective heat transfer (W)
Q_{loss}	Backward heat transfer (W)
Q_{pan}	Total net heat transfer (W)
Q_{rad}	Radiant heat transfer (W)
Q_{tot}	Total net heat transfer (W)
$\dot{q}_{con}$	Convective heat-flux density ($W\,m^{-2}$)
$\dot{q}_{loss}$	Backward heat-flux density ($W\,m^{-2}$)
$\dot{q}_{rad}$	Radiant heat-flux density ($W\,m^{-2}$)
$\dot{q}_{tot}$	Total heat-flux density ($W\,m^{-2}$)
T_a	Air temperature (°C)
T_{AUST}	Area weighted average unheated surface temperature (°C)
T_j	J-surface temperature (°C)
T_{op}	Operative temperature (°C)
T_s	Surface temperature (°C)
T_w	Water temperature (°C)
U	Coefficient of thermal transmittance of surfaces ($W\,m^{-2}\,K^{-1}$)
w_R	Error rate
ε	Emissivity
σ	Stefan-Boltzmann constant ($W\,m^{-2}\,K^{-4}$)

Abbreviations

BIM	Building information and modeling
C	Ceiling
CFD	Computational fluid dynamics
HRC	Heated radiant ceiling
HRW	Heated radiant wall
HTC	Heat transfer coefficient
HVAC	Heating ventilating air conditioning
RWCI	Radiant wall-Ceiling integrated
W	Wall

design restrictions on the actual cooling performance of the panel. Although radiant systems are prevalently used in new buildings, problems still remain in the calculation of cooling/heating capacity during the design process and this may cause an increase in energy consumption [14]. For the aim of the system sizing, global standards recommend the total HTCs (h_{tot}). In EN 1264-5 standard, the value of h_{tot} for heated ceiling is recommended to be in the range of 6–6.5 $W\,m^{-2}\,K^{-1}$ [15].

However, for more precious and accurate thermal performance examination of radiant systems, radiant HTC (h_{rad}) and convective HTC (h_{con}) values, which are the components of h_{tot}, have to be determined properly. Thereby, the convective HTC indicates the heat transfer between conditioned surface and room air. In the literature, various correlations of heat transfer coefficients are reported. Min et al. [16], Khalifa [17–19] and Awbi et al. [20–22] conducted experiments in a real-scale test room to examine the convective heat transfer and evaluated general convective heat transfer correlations.

Radiant heat transfer between the heated/cooled surface and all other surfaces is characterized by radiant heat transfer coefficient was investigated in some of recent studies. Feustel and Stetiu [23] evaluated HTCs of cooled ceiling and proposed the values of 9–12 $W\,m^{-2}\,K^{-1}$ for total heat transfer coefficient, which is comprised of radiant heat transfer coefficient of 5.5 $W\,m^{-2}\,K^{-1}$ and convective heat transfer coefficient of 3.5-6.5 $W\,m^{-2}\,K^{-1}$. Olesen [24] reported that more than 50% of the total heat exchange is through radiation (~5.5 $W\,m^{-2}\,K^{-1}$) in radiant floor heating, where the total HTC is the range between 9 and 11 $W\,m^{-2}\,K^{-1}$. On the other hand, in his work the proposed total HTC is 7 $W\,m^{-2}\,K^{-1}$ for cooling operation, while the radiant HTC is approximately 5.5 $W\,m^{-2}\,K^{-1}$. Therefore he also reported that, the value of 5.5 $W\,m^{-2}\,K^{-1}$ for radiant HTC can be applied to the all cases of radiant systems without any dependence to type of arrangement and operation mode. Causone et al. [25] measured the convective, radiative and total HTCs in an experimental test set-up facilitated with radiant system simulates the typical conditions of occupancy. They reported that radiant HTC of heated and cooled ceiling can be considered constant at 5.6 $W\,m^{-2}\,K^{-1}$ which is very similar to the ones proposed by Olesen et al. [24]. Moreover, he proposed average total HTC values of 13.2 $W\,m^{-2}\,K^{-1}$ and 5.8 $W\,m^{-2}\,K^{-1}$, respectively for the cooled and heated ceiling. Andres-Chicote et al. [26] carried out experimental study on the HTCs of a cooled radiant ceiling. They reported the approximate average values of 4.2 $W\,m^{-2}\,K^{-1}$ and 5.4 $W\,m^{-2}\,K^{-1}$ respectively for the convective and radiant heat transfer coefficients. Koca et al. [27] evaluated the HTCs of heated radiant wall in a test room using three different wall configurations. In their study, convective and radiant HTCs were respectively found approximately 5.7 $W\,m^{-2}\,K^{-1}$ and 2.7 $W\,m^{-2}\,K^{-1}$ as averages of the three different cases. Cholewa et al. [28] stated that the reported HTCs for radiant systems are overestimated. They estimated the convective HTCs of the radiant floor as 2.2-3.5 $W\,m^{-2}\,K^{-1}$ for heating and 0.0–0.1 $W\,m^{-2}\,K^{-1}$ for cooling which are 24% lower than the previously proposed ones. Moreover, radiant heat transfer coefficients were proposed as 5.0 $W\,m^{-2}\,K^{-1}$ for floor cooling and 5.6 $W\,m^{-2}\,K^{-1}$ for floor heating. Zhang et al. [29] proposed a simplified calculation method for the estimation of radiant floor heating/cooling capacity and then they validated the calculation results with well-known experimental results. Zhang et al. [30] conducted several experiments for the determination of heating and cooling capacity and HTCs of ceiling radiant panels. They proposed radiant HTC as around 5.5 $W\,m^{-2}\,K^{-1}$ which is the similar to the ones reported in [23–28].

2. Objectives

Up to now, many researchers has evaluated the HTCs of radiant floor and radiant ceiling (here in after HRC) systems, but very limited work have been performed to study the HTCs of heated radiant walls (here in after HRW) (Koca et al. [27]). Therefore, our first goal is to evaluate the heat transfer performance and HTCs of both HRW and HRC systems.

Despite the fact that radiant HTCs were obtained as approximately 5.5 $W\,m^{-2}\,K^{-1}$ in the previous studies ([6,25,30]), uncertainties – which are caused by the convective heat transfer – still remain. Therefore, reported convective HTCs in the previous studies vary in a wider range compared to the radiant and total HTCs. Furthermore, convective heat transfer significantly affects the total heat transfer which consists of both convection and radiation and has a critical role in the sizing process of the radiant systems. For this reason, our second objective is to provide further experimental evidence to better understand the heat characteristics of HRW and HRC systems and propose relevant heat transfer coefficients which can be used in heating capacity estimations. The results were examined and compared with those in the literature.

Many of the previous studies have been motivating radiant floor and ceiling heating-cooling systems except the one experimen-