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Thermal performance evaluation of hybrid heat source radiant system using a concentrate tube heat exchanger

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ABSTRACT

This study developed a new radiant system concept having a concentric tube heat exchanger embedded in a radiant panel and evaluated the system characteristics. The concentric tube heat exchanger allows two fluids, air and water, to flow in the same direction. The outdoor air for the space ventilation requirement passes through an inner tube. The primary heat transfer medium, water, flows through the outer tube exchanging heat with both radiant panel and air tube. Two fluids would have an identical temperature condition by the characteristics of the heat exchanger. The system configuration enables simultaneous satisfaction of the space sensible loads and ventilation requirement. It has also flexibility to use outdoor air directly at night to reduce any heat built up during the day in the thermal mass. A numerical analysis model based on computational fluid dynamics (CFD) has evaluated this conceptual system. Comparing this new system with the performance of a typical system incorporated with a dedicated outdoor air system (DOAS), the proposed system is shown to provide a more closed the room set temperature condition and a better local thermal environment. In addition, the developed system can improve the performance of the night ventilation operation using nocturnal outdoor air.

1. Introduction

Radiant panel systems use controlled temperature surfaces such as the floor, walls or the ceiling to maintain thermally comfortable conditions within spaces. These surface temperatures are maintained by circulating heat transfer media like water or air or by using electric resistance [1]. The systems have been reported to have advantages in improving occupants' thermal comfort and reducing heating and cooling energy consumption [2,3]. It was also the main focus of International Energy Agency (IEA) ECBCS Annex 37: low exergy systems for heating and cooling buildings [4]. Although the conventional radiant system has advantages for the occupants' thermal comfort and energy saving, it has also drawbacks to be overcome such as the start-up issue due to high thermal mass, sensible load only control, potential system interrupt due to surface condensation in cooling mode, and satisfaction of ventilation requirements.

Many researches have pointed out that conventional radiant systems need to be incorporated in conjunction with a convective forced air system to minimize the shortcomings. McDonell [5] claims that radiant heating and cooling systems alone may not serve as a perfect space conditioning system because there are three human comfort parameters: radiation comfort (40% to 50% of the human comfort equation), air movement (30% of the human comfort equation) and indoor air humidity (10% to 15% of the human comfort equation). Therefore, the radiant system must be integrated with a forced-air system to improve occupant's thermal comfort and minimize the possibility of condensation (radiant cooling systems only). Additionally, the author presented some practical data for the radiant heating and cooling capacity and concluded that the radiant cooling system can be designed to work in nearly all applications and most climate zone without fear of condensation when combined with a conventional air system that deals with outdoor air requirements. Oxizidis and Papadopoulos [6] also pointed out that a hybrid system, radiant floor panel incorporated with forced air system, provides a better thermal environment with relatively low energy consumption than other systems in cooling period.

There have been various attempts to decouple the outside air load due to ventilation requirements from the space conditioning load to avoid oversizing the HVAC system [7–9]. According to the accepted definition of this type of load-sharing or hybrid system, a radiant system is combined with a conventional forced air system to provide the conditioning needs of the space. In this case, the radiant system takes over most or all of the space sensible cooling while the air system controls the latent load and outdoor air requirements. One convective forced air system designed to

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Nomenclature

ρ	density (kg/m^3)
k	thermal conductivity (W/m K)
c	specific heat (J/kg K)
$\dot{m}$	mass flow rate (kg/s)
q_h	slab heating load (W/m^2)
q_c	slab cooling load (W/m^2)
σ	standard deviation
U-value	overall heat transfer coefficient (W/m^2 K)
ACH	air change per hour

control the ventilation requirement is the dedicated outdoor air system (DOAS). It is 100% outdoor air constant volume system designed to deliver the volumetric flow rate of ventilation air to each conditioned space in the building. Mumma et al. [10,11] developed the system concept and has been implemented them in buildings since the late 1980s. The authors proposed and evaluated DOASs in conjunction with a cooling radiant ceiling panel (CRCP) system. This system combined an outside air control system and metal CRCP. According to steady-state simulation results comparing this combination system with a conventional VAV system, the DOAS with CRCP system can reduce the annual total chiller energy consumption by 25%. Although the authors showed remarkable potential for the DOAS with CRCP system as an energy conserving alternative, it can been argued that implementation of this system requires at least eight different components to make the system work properly. This increases the initial cost and makes system control and maintenance more difficult. In addition, the cooling or heating demand might not be offset using potentially less expensive off-peak energy because the CRCP is composed of a metal panel so that the system has little to no thermal mass effect.

Kilkis [12] developed an analytical model for a hybrid heating and cooling terminal unit composed of a perforated metal deck and raised floor air chamber. Outside air or room return air passes through the plenum space of the raised floor and diffuses through the perforated holes of the metal deck. The deck acts as a typical radiant system but its convective heat transfer is enhanced by air passing through the perforated holes. Based on this system design, the author suggested the optimal design parameters for this system for the renovation of an old library building. Although this seems like an effective method to improve the capacity of an existing HVAC system for an historic building, the author also claimed that the system has several challenges such as concerns about condensation which require surface temperature control of the metal deck, mold-growth in the porous carpet, chemical and dust effect of the carpet, air flow direction, and handling water from condensation in the air plenum.

The benefits of the radiant system in conjunction with a forced-air system have been evaluated by several field measurement studies. Baskin tested the heating and cooling energy performance of a residential house with both a radiant and a convective air system. The pre-cooling operation of the radiant slab was effective in reducing the cooling demand and shifting it from the on-peak time to early morning (off-peak). If the radiant slab was pre-cooled with the night ventilation operation of the convective air system, the energy demand of the daytime would be shifted to the nighttime [13–16].

This strategy is helpful in locations where the local power company supplies electrical power at a reduced rate during off-peak/nighttime periods. Scheatzle [17] monitored a residential building with a radiant system and heat recovery unit with dehumidifier for four years in a hot and arid climate. According to the author's findings, the thermally massive radiant heating and cooling system combined with convective dehumidification/ventilation can be an effective system option for a residential building.

Based on previous work, the performance of a radiant system can be enhanced when it is integrated with a convective forced air system for outside air control. However, it requires additional work to control the two different system types and additional space for the air handling unit. Furthermore, its inherent complexity makes it a more difficult HVAC system to design and size when the two systems use different heat transfer media.

The purpose of this study is to design a new radiant system that can satisfy the ventilation requirement and space thermal load simultaneously. It verifies the thermal performance of the proposed system by comparing a convective forced air system integrated with a conventional hydronic radiant system based on numerical analysis.

2. Concept development

2.1. Background

Even though a radiant panel heating and cooling system can be categorized by the heat transfer media types, the thermal characteristic of building components used as the radiant panel, and the construction layout, a hydronic radiant system with water tubes embedded in a concrete panel is the primary focus of this study.

There are two considerations in the design and construction of a hydronic radiant system. First, the tubes of typical embedded hydronic radiant systems are constructed as continuous tubes. The spacing of the tubes ranges from 150 mm to 450 mm on centers [1]. The total tube length will range from 2 m to 6 m per unit area (m^2) of a radiant panel. If the tube, which is embedded into the slab, has a diameter of 15 mm, the contact surface area is in-between 0.094 m^2 and 0.28 m^2 inside of the panel. This provides a relatively large heat exchange area between the water loop and floor slab.

Second, the water temperature of a hydronic radiant system is restricted to avoid excessively hot or cold surface temperatures. It is common to design for an 11 °C temperature drop for heating across a given system grid and a 3 °C rise for cooling. However, the surface temperature for a radiant floor heating system in an occupied space is recommended to be between a lower limit of 19 °C for cooling and an upper limit of 29 °C for heating to avoid thermal comfort problems associated with too hot or too cold surfaces [18]. This means that the supply and return water temperature are often around 35 °C and 29 °C, respectively, for heating and 20 °C and 19 °C, respectively, for cooling.

From these design guidelines for hydronic radiant systems, it is possible to conclude that the temperature of the heat transfer medium (water) of a radiant system is lower for heating and higher for cooling than a conventional forced air system. It can also be seen that the radiant system has a relatively large surface area to exchange heat between the tube and panel. Applying these guidelines to the concentric tube radiant system with the water exchanging heat with both the slab and the air loop simultaneously and assuming that the air can exchange heat completely with the water tube, we can anticipate that the outlet temperature of the air will be approximately 29 °C for heating and 19 °C for cooling. Outlet air temperatures within this range would not only provide for conditioning of outdoor air to meet the ventilation requirement, but it would also reduce the space thermal loads by convective heat transfer when delivered into the space. These arguments and the relative simplicity of the concentric tube radiant system when compared to the combined radiant/DOAS system provide the basis for the conceptual development described in the sections that follow.