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Evaluating the low exergy of chilled water in a radiant cooling system

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ABSTRACT

In this paper, in order to make guidelines for designing a low-energy radiant cooling system with an air-handling unit (AHU) for dehumidification, we investigated the impact of various air-conditioning parameters on the exergies of chilled water supplied to radiant panels and a cooling coil. The cooling load, thermal comfort index PMV, relative humidity, area of radiant panels, sensible heat factor (SHF), temperature and air-flow rate of supply air of the AHU, and presence/absence of total heat exchanger were considered. We used computational fluid dynamics (CFD) code in order to analyze the indoor air-flow and thermal environments, and added models for the calculation of thermal transfer to radiant panels and a cooling coil. Furthermore, a feedback control algorithm was introduced to calculate the surface radiant panel temperature, targeting the average PMV of the task area in an office room. As a result, the impact of various air-conditioning parameters on the exergies of chilled water were demonstrated quantitatively. As an example, by reducing the cooling load rate from 100% to 57% and 27%, the exergy of chilled water decreased by 47% and 67%, respectively.

1. Introduction

In comparison with convective cooling systems, radiant cooling systems generally have uniform room air temperature distributions and heat exchange by radiation between a human body and his or her surrounding environment. For energy conservation, radiant cooling systems have more advantages than convective cooling systems. These advantages have been shown in many papers. In order to investigate the various characteristics of radiant ceiling systems and their practical application to office buildings, Imanari [1] compared a radiant ceiling system and conventional air-conditioning system in terms of thermal comfort, energy consumption and cost. The results showed that, due to the smaller supply air volume, the radiant ceiling system shows lower mean air velocity and smaller PDs (percentage of dissatisfied) than the conventional system using air-handling unit (AHU). Through simulation, it is known that energy consumption can be reduced by 10%. The estimated payback time is 1–17 years, depending on the market price of radiant ceiling panels. Vangtook [2] reported an experimental and simulation study of an application of radiant cooling using natural air for ventilation under hot and humid climates. The result shows that the temperature of water supplied to the panel must be limited to 24 °C to avoid condensation of moisture on the cooling panel. Zmrhal [3] described modeling and simulation of a space with a radiant cooling ceiling. The main goal was to determine the conditions of thermal comfort of occupants in a room with a cooling ceiling and various heat gains. The paper also presented the influence of room height on thermal comfort. The results showed that the tendency of thermal comfort in a room with a radiant cooled ceiling is dependent on operative temperature and activity level. The cooling ceiling system is more effective in the low height room. Loveday [4] stressed that the current design standard BS EN ISO7730 is based on the work of Fanger. The model was derived from laboratory-based measurements conducted in the mid-1960s in relatively "conventional" environments. However, a chilled ceiling operating in combination with displacement ventilation represents a more sophisticated environment in comparison with the conditions in which the original Fanger model was derived. This raised a question about the applicability of the current standard when designing for thermal comfort in offices equipped with chilled ceiling/displacement ventilation systems. Loveday's paper sought an answer the above question regarding the standard. It was shown that the current standard BS EN ISO 7730 may be used, without modification, when designed for the thermal comfort of sedentary workers in offices equipped with a chilled ceiling/displacement ventilation system.

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Feustel [5] investigated many papers about hydronic radiant cooling (HRC). In their cooling performance discussion, they pointed out that a radiant temperature asymmetry of 10 °C and 14 °C is acceptable in the presence of a cool wall and in the presence of a cooling ceiling, respectively. In their energy-saving section, they mentioned that the energy conservation peak-power reduction of the HRC system particularly suited dry climates, and the electrical energy for fans and pumps can be reduced to approximately 25% of the original value. In the peak-power section they mentioned that the HRC system uses only about 72% of the total electrical power required by the all-air system. Finally, they summarized the reviewed literature by stating that HRC systems provide draft-free cooling, reduced space requirements, increased indoor air quality, reduced energy consumption for thermal distribution and for space conditioning, and might even have a lower initial cost if specific cooling loads are above 55 W/m^2. They also mentioned that unfortunately, literature has not been found which describes the dynamic thermal behavior of the system and the building. Dynamics might be an important issue in further studies because the comfort temperature in a space is not only dependent on the air temperature but also on the (dynamic) distribution of the surface temperature in the space.

In our study, although we did not consider dynamics, we investigated many parameters in order to formulate guidelines for designing a radiant cooling system. Therefore, we tested varying air-conditioning parameters to investigate their influence on the exergies of chilled water supplied to radiant panels and cooling coil systems. For example, we changed the indoor cooling load to 27%, 57% and 100% (we expected that the maximum cooling load was 100%); the thermal comfort PMV index from −0.5 to +0.5; relative humidity of the room to 50%, 55% and 60%; the area of radiant panels to 1 m^2 per unit area of floor, 1.18 m^2 per unit area of floor, and 1.32 m^2 per unit area of floor; the sensible heat factor (SHF) to 0.85, 0.90 and 0.95; the supply air temperature to 21 °C, 23 °C and 25 °C; the air-flow rate of AHU to 18.3 m^3/h m^2, 26.7 m^3/h m^2 and 35 m^3/h m^2; and the presence or absence of a total heat exchanger.

The estimation of energy consumption of the whole air-conditioning system needs detailed specifications of capacity, type of chiller, characteristics of the chiller, designing of the ducts and fans, resistance of the piping, capacity of the pump, and so on. But, generally, this level of detail is too complicated and we often cannot say the specifications are universal because the characteristics of machines often depend on the manufacturer. For these reasons, we evaluated the energy consumption by the simple and universal exergy of chilled water produced by chillers. This is possible because the exergy of chilled water used in this study is the theoretical necessary power of the reverse Carnot cycle of the chiller, which removes the cooling load of a room. We then added up these values as the exergy of chilled water of the whole system. Using this exergy value, we evaluated the energy consumption of various air-conditioning parameters.

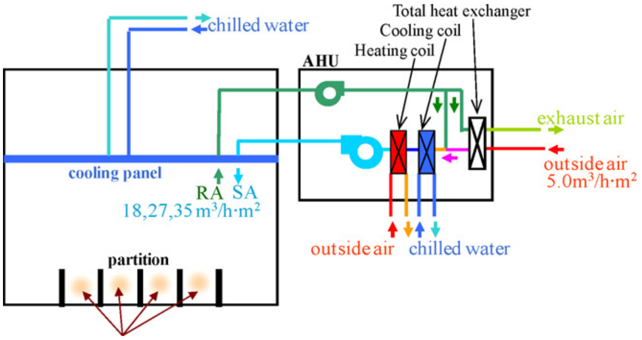

Fig. 1. Radiant panel cooling system with AHU.

2. Description of the setup of the radiant cooling system

Our radiant cooling system configuration is shown in Fig. 1. Inside the room in this system, there are a ceiling cooling panel, five small partitions of radiant panels in the center of the room and a large partition of a radiant panel in the other side of the room with a functional small partition side (shown in Fig. 2). The ceiling and partition panels are cooled by chilled water. In addition, there is an AHU, which is constructed by a total heat exchanger, cooling coil and heating coil. The mixture of outdoor air and return air is cooled, dehumidified and reheated by the AHU, then supplied to the room.

Our model of an office room (10 m × 6 m × 2.7 m) is shown in Fig. 2. It is assumed that the maximum cooling load is set for the following: a Japanese summer, two printers and four PCs (total 1300 W) on a long table located near the center of the office room. These heat sources are set on the surface of the printers and PCs. It is also assumed that two copy machines are in the room, and their heat sources are set on the floor. Furthermore, it is assumed that four people are operating the PCs all the time, and the sensible heat sources (46.5 W/person) of the people are set in the air cells of four task areas (1.3 m × 1.15 m × 1.2 m). Eight other people are considered to exist in the room, and their sensible heat sources are set in every air cell except the task areas. Ten lights (total 1744 W) are located across the entire ceiling. The heat source of

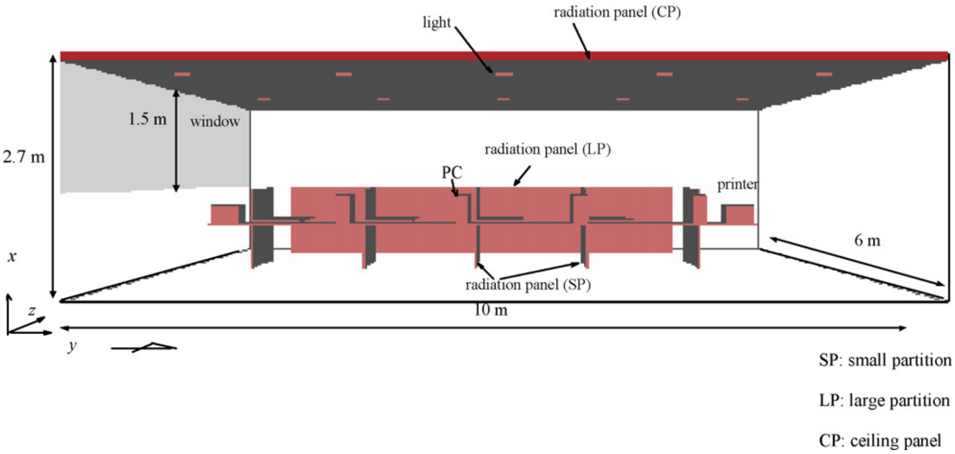

Fig. 2. Model of an office room.