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Entransy analysis and application of a novel indoor cooling system in a large space building

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ABSTRACT

Researchers are giving increased attention to large space buildings such as airports and railway stations because of the high energy consumption of their indoor cooling systems. The indoor cooling system of a large space building is essentially a heat transfer process among several heat sources and heat sinks. Entransy analysis and *T*–*Q* diagrams are clear and direct methods for describing the heat transfer process in large space buildings. Based on entransy dissipation, the equivalent thermal resistance can be defined in order to evaluate the indoor cooling systems in large space buildings. Minimizing thermal resistance is the best way to achieve high-temperature cooling. Methods for reducing the equivalent thermal resistance from the heat sources to the heat sinks in large space buildings include simplifying the heat transfer process, reducing mixture loss among heat sources, minimizing unnecessary mixing of hot and cold fluids, and handling solar radiation directly. Based on this analysis, a radiant floor and displacement ventilation system is proposed. Compared with a conventional jet ventilation system, the radiant floor system has lower equivalent thermal resistance, especially for direct solar radiation. The new system was applied in Xi'an Xianyang International Airport, and it demonstrated approximately 34% better energy performance compared to the conventional system.

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1. Introduction

Researchers are giving increased attention to large space buildings such as airports and railway stations. The energy consumption of the HVAC systems in large space buildings is very high due to the buildings' height and span, transparent building envelope, dense occupancy, and long hours of operation. Most HVAC systems in large space buildings are jet ventilation systems, which cause significant indoor mixture loss and result in a high energy consumption of fans [1].

Many studies have examined the indoor environment of large space buildings and proposed new forms of ventilation. Nishioka et al. [2] presented measurements of the indoor thermal environments in a large domed stadium; the vertical temperature distribution indicated that the under-seat supply air-conditioning system only provided air-conditioning to the occupant zone. Said et al. [3] described thermal stratification in eight aircraft hangar buildings during the heating season, and concluded that thermal stratification had a significant impact on the buildings' heating energy requirements. Chow et al. [4] presented an experimental study of air speed induced by mechanical ventilation in the occupied zone of seven railway stations. Huang et al. [5] carried out on-site measurements of a stadium in summer, winter, and transitional seasons; the results indicated that the energy savings of the upper openings varied in different seasons. Displacement diffusers were introduced by Olesen [6] in an airport application. Lau and Chen [7] compared the energy use of a floor-supply displacement ventilation system with that of a mixing ventilation system in a large industrial workshop.

Radiant heating and cooling systems possess the advantages of thermal comfort and highly efficiency heat transportation. Olesen [6] introduced the application of radiant floor cooling systems in airports. In spaces where the sun shines directly on the floor (e.g., atriums, entrance halls, showrooms, etc.), the cooling capacity is significantly higher (up to 100 W/m^2). Song et al. [8] evaluated the performance of a radiant floor cooling system integrated with dehumidified ventilation through both experiments and simulation. It was found that the proposed system was not only able to solve the problem of condensation; it also improved the responsiveness to internal load changes. In another study, a temperature and humidity independent control (THIC) system was implemented

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Nomenclature

A	heat transfer surface area (m^2)
c_p	specific heat (J/(kg K))
En	entransy (kJ °C)
h	specific enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
Q	heat (kJ)
Ra	gas constant (8.314 kJ/(k mol))
R	equivalent thermal resistance (°C/kJ)
s	specific entropy (kJ/(kg K))
T	temperature (°C)
U	overall heat transfer coefficient (W/(m^2 K))
V	velocity vector (m/s)
ω	humidity ratio (g/kg)
ξ	unmatched coefficient

Subscripts

0	reference condition
a	air
c	convection
o	obtained entransy
r	radiant floor
s	supplied entransy
sa/ra	supply air/return air
sw/rw	supply water/return water
Φ	entransy dissipation

and tested in the atrium of an office building [9]. It was shown that radiant floor cooling and separate humidity control increased the temperature of the chilled water and improved system efficiency.

A more efficient utilization of energy is desirable in large space buildings. Using a low supply water temperature in heating conditions (e.g., 25–40 °C) and a high water temperature during cooling (e.g., 16–20 °C) can increase energy efficiency, allowing for the use of renewable energy sources [10] such as ground heat exchangers or cooling towers in cooling conditions. Reducing the heat transfer loss from the heat sources to the heat sinks is an effective way to achieve high-temperature cooling and low-temperature heating in large space buildings. In order to evaluate the heat transfer process quantitatively, Guo et al. [11] introduced the novel physical parameter of entransy, which measures heat transfer ability. Based on this parameter, Guo et al. [12] later introduced entransy dissipation and equivalent thermal resistance. Entransy is a useful tool for optimizing the heat transfer process, including heat conduction, convective heat transfer, and radiant heat transfer. Chen et al. [13] presented the equivalent thermal resistance of a heat exchanger couple based on entransy dissipation. Chen et al. [14] studied convective heat transfer and concluded that the entransy dissipation extremum principle yields the maximum convective heat transfer efficiency. Cheng and Liang [15] developed the concept of entransy flux for thermal radiation in enclosures with opaque surfaces and derived the minimum principle of radiant entransy dissipation. Shan et al. [16] proposed a three-step strategy for optimizing the geometries of various self-similar transport networks based on entransy theory.

The indoor cooling system of a large space building is essentially a heat transfer process among several heat sources and heat sinks. Entransy analysis provides a new perspective with which to examine the heat transfer process, especially loss during heat transfer. Entransy dissipation is a quantitative parameter that is used to evaluate losses in the heat transfer process; reducing entransy dissipation is the best way to achieve high-temperature cooling. In this paper, methods for reducing entransy dissipation or equivalent thermal resistance are suggested, and a new system consisting of a radiant floor integrated with a temperature and humidity independent control (THIC) system is proposed. This novel system is then applied in Xi'an Xianyang International Airport.

2. The characteristics of the built indoor environment in large space buildings

The characteristics of the indoor environment in a large space building can be summarized as follows: (1) a high and large-span structure of space, temperature, and humidity stratification in the vertical direction [1,2,5]; (2) intensive solar radiation caused by a large transparent building envelope [6]; (3) high-temperature envelope surfaces caused by solar radiation [1], heat sources such as heat transfer from the envelope, and equipment and human beings above the ground; (4) the air-conditioning region is less than 2 m above the floor in order to satisfy the requirement of human comfort.

There are four main heat sources in large space buildings: direct solar radiation through the transparent building envelope, the building envelope, equipment, and human beings. The humidity in large space buildings mainly comes from human beings. Fig. 1 shows the typical temperature level of different heat sources in large space buildings. The temperature of the building envelope can reach 40 °C for skylights with solar radiation. The temperatures of lights, advertising boxes, and other devices fall into a relatively wide range of 30–50 °C. In addition, direct solar radiation is a special kind of heat source that can be absorbed by inner surfaces. Fig. 2 shows the schematic diagram of a traditional system in a large space building, and the air handling process is illustrated in Fig. 1. The system uses jet ventilation to remove all the heat from the indoor environment, which mixes all the heat into the room air at approximately 26 °C. Typical jet supply air outlets in the indoor environment are shown in Fig. 3. The heat transfer process from the heat sources to the chilled water includes several steps: convective heat transfer from the heat sources to the indoor air; mixing the supply air with the indoor air; mixing the return air with the fresh air, and heat exchange of the air with the chilled water in the air handling unit. The basic heat transfer processes of HVAC

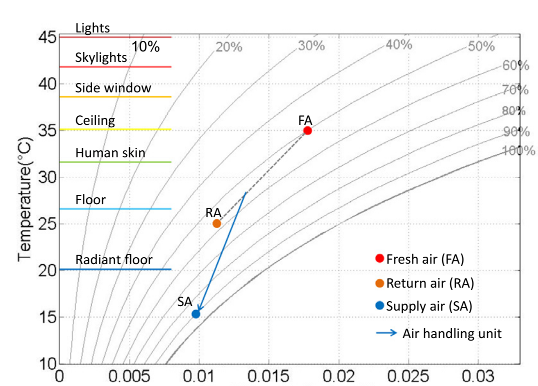

Fig. 1. Temperature of heat sources and air handling process in psychrometric chart.

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