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Energy saving potential of heat removal using natural cooling water in the top zone of buildings with large interior spaces

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ABSTRACT

Generally, ventilation with outdoor air is used to directly remove heat in the top zone of large-space buildings to conserve energy. However, this will increase the latent cooling load because a large amount of humidity can be introduced to the interior when the outdoor air is humid. Therefore, a new method that incorporates a natural cooling water system in the top zone and does not introduce moisture is proposed in this study. The cooling tower as the source of natural cooling water and dry fan coil units (FCUs) as the terminal of removing heat were selected as an example of this new method. In order to analyze the energy saving potential of the new method, 9 cases involving different heat source distributions and cities were simulated by CFD, and 3 more cases with the traditional method were discussed. The results show that the traditional method increases the system energy consumption when the outdoor air humidity is high, and the biggest growth rate is 57.4%. But, the new method can be applied in different cities and in different heat source distributions, and can achieve a considerably high energy saving rate, ranging from 5.2% to 21.4%. The energy saving rate increases as the heat source ratio between the bottom zone and top zone decreases, because more heat can be removed by the dry FCUs. The energy saving rate varies by city, due to the different cooling water temperature. This new method will help guide the design of HVAC systems in large-space buildings.

1. Introduction

According to Annex 26 in the International Energy Agency (IEA) project, a large-space building is defined as an enclosed ventilated air space that is partly occupied and contains various heat and contaminant sources [1]. Recently, large-space buildings have begun to develop quickly in the world and have become very popular in the design of modern buildings. Large-space buildings include not only civil buildings, such as atria, shopping malls, concert halls, sports centers, railway stations, and airport terminals, but also industrial buildings, such as various manufactories, warehouses, mines, refineries, and power plants. Due to the large height and width of the space, large ratio of external walls to interior walls, dense occupancy, abundance of equipment, and long-time operation, the energy consumption in large-space buildings is high, and most of it dedicated to the heating, ventilation, and air conditioning (HVAC) system [2–8]. As a result, research on the energy saving potential of HVAC in large-space buildings is attracting increasing attention.

Thermal stratification is common in large-space buildings, and has been measured on-site and confirmed in real buildings, such as a hospital hall [9], stadium [10,11], aircraft hangar [12], airport terminal [13], power plant [14], and industrial factory [15]. Usually, only a small portion of the entire volume is occupied in large buildings, and high energy efficiency may be achieved by directing conditioned air only to the occupied zone. Therefore, the stratified air-conditioning system, first proposed in the 1970s, is a common choice for large-space buildings. This type of system guarantees that the occupied zone at the bottom to be thermally comfortable and offer acceptable indoor air quality (IAQ) by supplying cooling air at a speed of 3.0–7.5 m/s at a height of 3–5 m [9,16–22]. Because of the thermal stratification effect and the large number of high temperature heat sources, such as solar radiation, strong lights, large screens, and electronic panels, the air temperature in the top zone could be very high (>40 °C) [10,14,18,23]. The heat suspended

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Nomenclature

U	overall heat transfer coefficient, W/(m^2·°C)
A	heat exchanger area, m^2
T_w	cooling water temperature from cooling tower, °C
m	mass air flow rate of dry fan coil units (FCUs) or ventilation in the top zone, kg/s
T_s	supply air temperature from inlets in the bottom zone, °C
m_s	supply air flow rate from inlets in the bottom zone, kg/s
V_s	supply air velocity from inlets in the bottom zone, kg/s
V_{s_fnl}	final supply air velocity from inlets in the bottom zone, kg/s
d_s	supply air humidity from inlets in the bottom zone, g/kg
d_{s_fnl}	final supply air humidity from inlets in the bottom zone, g/kg
T_{oz}	average air temperature in the occupied zone, °C
RH_{oz}	average air relative humidity in the occupied zone, %
T_{in}	intake air temperature of dry FCUs in the top zone, °C
T_{re}	return air temperature of dry FCUs in the top zone, °C
T_{vent}	supply air temperature of ventilation in the top zone, °C
T_{ex}	exhaust air temperature of ventilation in the top zone, °C
m_f	mass flow rate of fresh air, kg/s
c_p	specific heat capacity of air, kJ/(kg·°C)
h_{set}	specific enthalpy of the air in the occupied zone with set temperature and humidity, kJ/kg
h_s	specific enthalpy of supply air from inlets in the bottom zone, kJ/kg
h_f	specific enthalpy of fresh air, kJ/kg
Q_{btm}	cooling load in bottom zone, W
Q_{top}	cooling load in top zone, W
Q_f	fresh air cooling load, W
Q_{tot}	room cooling load, W
Q_{btm+f}	cooling load in bottom zone and fresh air cooling load, W
Q_{sys}	system cooling load, W
N_{sys}	energy consumption of air conditioning system, W
N_{btm}	energy consumption in the bottom zone, W
N_{top}	energy consumption in the top zone, W
N_{ch}	energy consumption of chiller in the bottom zone, W
N_{cp}	energy consumption of cooling water pump in the bottom zone, W
N_{ct}	energy consumption of cooling tower in the bottom zone, W
N_{chp}	energy consumption of chilled water pump in the bottom zone, W
N_{AHU}	energy consumption of air handle unit (AHU) in the bottom zone, W
N_{cp}^{top}	energy consumption of cooling water pump in the top zone, W
N_{ct}^{top}	energy consumption of cooling tower in the top zone, W
N_{FCU}	energy consumption of dry FCUs in the top zone, W
N_{VENT}	energy consumption of ventilation in the top zone, W
$EERt_{AHU}$	energy efficiency ratio of AHU
WTF_{cw}	water transfer factor of cooling water
WTF_{ct}	water transfer factor of cooling tower
WTF_{chw}	water transfer factor of chilled water

Subscripts

w	cooling water temperature from cooling tower
s	supply air temperature from inlets in the bottom zone
fnl	final
oz	occupied zone
in	intake air of dry FCUs in the top zone
re	return air of dry FCUs in the top zone
vent	supply air of ventilation in the top zone
ex	exhaust air of ventilation in the top zone
f	fresh
set	set
btm	bottom
$btm + f$	bottom and fresh
top	top
tot	total
sys	system
ch	chiller
cp	cooling water pump
ct	cooling tower
chp	chilled water pump
cw	cooling water
chw	chilled water
FCU	dry FCUs in the top zone
VENT	ventilation in the top zone

Abbreviations

CFD	computational fluid dynamics
FCU	fan coil unit
HVAC	heating, ventilation, and air conditioning
EERt	energy efficiency ratio of terminal
COP	coefficient of performance
WTF	water transport factor

in the top zone will then have a significant influence on the occupied zone through the effects of radiation and convection. Generally, natural or mechanical ventilation with outdoor air is used to directly remove the heat in the top zone to conserve energy [4,16,24,25]. This traditional method works well when the temperature and humidity of the outdoor air is lower than that of the air in the top zone. By simulated and experimental analysis, Wang et al. [26] found that deceasing the outdoor air temperature and reducing the height of the inlet location could increase the effective usage of natural ventilation in the top zone of large space buildings. Lin and Chuah [27] found that natural ventilation can be used for cooling large buildings that are located in subtropical climates. Karava et al. [28] reported that 30% of cooling load could be operated by natural ventilation in an atrium located in Montreal, Canada.

However, when the outdoor air is humid during the summer, a large amount of moisture will be introduced to the indoor environment, which will increase the latent cooling load. Under these circumstances, the traditional method of ventilating outdoor air to the top zone does not work. The Chinese climate, which is quite vast, varies by the location of the city. For example, in the Yangtze River area, the relative humidity is usually high, and can exceed 95% during summer [29,30]. Therefore, in order to effectively reduce the energy consumption required to cool large-space buildings, a new method should be developed that decreases the air temperature in the top zone without introducing moisture. If a heat transfer unit with natural