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Comparison of air-conditioning systems with bottom-supply and side-supply modes in a typical office room

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HIGHLIGHTS

- The bottom-supply mode and side-supply mode were studied contrastively.
- The simulation results were validated by the physical experiment in the laboratory.
- The indoor thermal environment, PPD and energy utilization efficiency were explored.
- The bottom-supply mode provided better thermal comfort and lower energy saving.

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ABSTRACT

The growing energy consumption and thermal comfort of an air-conditioned room have attracted increasing public attention. As such, the performance of air-conditioning systems with two air supply modes for a simplified office room was studied by numerical simulation and physical experiment. An experimental investigation was developed in an environmental chamber to validate the simulation model. Numerical investigation was carried out subsequently for an office setting by the validated CFD model. The indoor thermal environment, human thermal comfort and energy utilization efficiency of two air supply modes were analyzed and compared in this study. The results showed that under both air supply modes, thermal stratification occurred in the model room, and the air flow velocity in the occupied zone was low. In addition, the results indicated that under 21 °C supply temperature, the air-conditioning system with bottom-supply mode provided better indoor thermal comfort of the occupied zone, but the energy consumption was higher than the side-supply mode.

1. Introduction

The growing demands of more energy conservation and better thermal comfort have become major concerns in the building sectors. The energy in HVAC (Heating, Ventilation & Air Conditioning) systems accounts for a large proportion of the total building energy consumption [1]. In China, over 30% of the social energy is consumed in buildings. HVAC systems cover about 63% of the overall energy consumption in buildings [2–4]. Hence, the Asian countries proposed to increase the indoor air temperature in summer to reduce the energy consumption in buildings [5]. Thus, maintaining the indoor thermal comfort, increasing supply air temperature and lowering supply air velocity under different air supply modes have become a key point in the research field of the indoor environmental control.

The influence of ventilation system types, diffuser types and cooling technologies on the energy consumption and ventilation efficiency was studied by researchers [6–8]. Meanwhile, studies on the air-conditioning system for different kinds of buildings were carried out to analyze the comfort and energy saving [9,10]. Among the available ventilation systems, the stratified ventilation systems, such as under-floor air distribution system, displacement ventilation system and stratum ventilation system, provided considerable potentials in satisfying the main requirements of indoor air quality, thermal comfort and energy saving simultaneously. The performance of mixing ventilation system with ceiling-mounted inlets, confluent jets ventilation system and under-floor air distribution system in an open-plan office

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Nomenclature

Acronyms

CFD	computational fluid dynamics
HVAC	heating, ventilation and air conditioning
PMV	predicted mean vote
PPD	predicted percent dissatisfied
EUC	energy utilization coefficient

Variables and parameters

a_k	inverse effective Prandtl numbers for k
a_ε	inverse effective Prandtl numbers for ε
C	constant
f_{cl}	clothing surface area factor
F	external forces
G_b	generation of turbulence kinetic energy due to buoyancy
G_k	generation of turbulence kinetic energy due to the mean velocity gradients
h	sensible enthalpy
h_c	convective heat transfer coefficient
g	gravity
k	turbulence kinetic energy
k_{eff}	effective conductivity
M	metabolic rate
p	static pressure
p_a	water vapor partial pressure
S_h	total volume force
S	source terms
t_a	air temperature
t_{cl}	clothing surface temperature
t_{oz}	mean temperature in occupied zone
t_s	supply air temperature
t_{uz}	mean temperature in unoccupied zone
$\bar{t}_r$	mean radiant temperature
v	airflow velocity
W	effective mechanical power
Y_M	contribution of the fluctuating dilatation
ρ	fluid density
$\bar{\bar{\tau}}$	stress tensor
ε	rate of dissipation
μ_{eff}	turbulent viscosity coefficient

space was investigated experimentally. The results showed that the confluent jets ventilation system and under-floor air distribution system were more suitable for open-plan office due to higher air exchange efficiency and lower local mean age of air compared with the mixing ventilation system [11]. A comparative study of energy performance of mixing ventilation, displacement ventilation and stratum ventilation systems was carried out by Lee et al., which was applied to the traditional classrooms, study group and e-learning classrooms in a school. The study showed that, the stratum ventilation system was the best among the three kinds of ventilation systems used for schools in Hong Kong [12]. Bos et al. conducted a survey on indoor thermal comfort of an office building with under-floor air distribution in cold weather, and obtained acceptable temperature ranges and thermal comfort evaluation results of the staff activity area [13]. Ho et al. simulated and compared the performance of air-conditioning systems with top air supply mode and under-floor air supply mode in an office room. The results indicated that the performance of under-floor air supply mode was better than that of top air supply mode in removal of pollutants and energy saving under the same indoor thermal comfort conditions [14]. Experimental and theoretical studies were carried out in office buildings with under-floor air supply systems in the hot climates. The energy consumption of the under-floor air supply system was compared with that of the ceiling based air distribution system. It was found that the energy consumption of under-floor air supply system reduced 37–39% in July to September and 51% in October [15]. Numerical study suggested that the displacement ventilation system had better performance of air exchange efficiency and energy saving, but it provided a worse uniform distribution of air temperature because of the significantly vertical temperature gradient in the lower height of a standing person [16]. The thermal comfort and indoor air quality of mixing ventilation system and displacement ventilation system were compared experimentally by Shan et al. The experimental results showed that passive displacement ventilation led to significantly lower overall draft sensation but higher draft and colder sensation in the lower body level than mixing ventilation [17]. The indoor thermal environment, air quality, thermal comfort and energy efficiency of displacement ventilation system combining with chair fans were simulated and optimized by the validated CFD model. The simulation results revealed that the novel system with different optimal heights of fans provided 11.6–20.6% energy saving compared to the stand alone displacement ventilation system [18].

Based on the previous studies, this study addressed two types of air distribution systems, including bottom-supply mode system and side-supply mode system. Although there have been many studies on different kinds of air-conditioning systems, investigating its energy consumption and indoor thermal comfort in different supply modes, few studies compared and evaluated the performance of the air-conditioning systems under the bottom-supply mode and the side-supply mode used for office buildings. Based on the related research results, numerical simulation and experimental approach were adopted to study and compare the indoor thermal environment, human thermal comfort and energy utilization efficiency under the bottom-supply mode and the side-supply mode which could provide suggestions for optimization and design of air conditioning systems.

2. Experimental study

2.1. Experimental set up

An experimental laboratory for a simplified office with 6.0 m × 4.0 m × 3.5 m (length × width × height, X axis × Y axis × Z axis) was set up as shown in Fig. 1. For this laboratory, an experimental system with bottom-supply and side-supply modes was established. For the bottom-supply air-conditioning system, there were eight air inlets on the floor with six circle inlets and two rectangular inlets to ensure the comfort zone for occupants (see Fig. 2(a)). In addition, two rectangular air outlets were set on the ceiling. For the side-supply air-conditioning system, there were four inlets on the side walls (see Fig. 2(b)) and the outlets were the same to the bottom-supply air-conditioning system. In the bottom-supply mode system, the circular inlets with the diameter of 200 mm were set at the middle zone of the test room, and the rectangular inlets with the length × width of 700 mm × 500 mm were set near the wall (see Fig. 2(a)). The rectangular inlets of the side-supply model system with the length × width of 800 mm × 600 mm were set at 1.2 m height on the side walls according to Ref. [19]. Air-values were set on each branch pipe to switch the operation system. In order to ensure the supply air flow rate of the two compared modes to be equal, the air valves were adjusted according to the supply air speed.

The total air-conditioning cooling load of the office was calculated according to the ASHRAE Handbook [20,21] and the air conditioning designs of civil buildings [22,23]. Heat transfer through the building