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A numerical study on the effects of exhaust locations on energy consumption and thermal environment in an office room served by displacement ventilation

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ABSTRACT

In an office room, many factors affect the pattern of airflow, thermal comfort, indoor air quality and energy saving. In this study, the effects of the location of exhaust diffusers where the warm and contaminant air is extracted and their relation to room heat sources on thermal comfort and energy saving were investigated numerically for an office served by a displacement ventilation system. The indoor air quality in the breathing level and the inhaled zone were also evaluated. The contaminants were released from window and door frames in order to simulate the contaminants coming from outside. The amount of energy consumption and the indoor thermal environment for various exhaust locations were investigated numerically using the computational fluid dynamics techniques. The results showed that the thermal indoor environment, thermal comfort, quality of indoor air and energy saving were greatly improved by combining the exhaust outlets with some of the room's heat sources such as ceiling lamps and external walls. In particular, a 25.0% of energy saving was achieved by combining the exhaust diffuser with room's ceiling lamps. In addition, locating the exhaust diffuser near the heat sources also reduced the cooling coil load by 13.8%. The risk of a large difference in temperature between the head and foot levels, increased particle concentration in the occupied zone, as well as increased energy consumption was also clearly demonstrated when the exhaust and recirculated air outlet (return opening) were combined in one unit in the occupied boundary area that is located at 2 m away from the occupants. Thus, for the optimum energy saving and better indoor environment, the combination of the indoor heat sources with the exhaust outlet is necessary.

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1. Introduction

One of the most important aims of the Heating, Ventilation and Air Conditioning (HVAC) system is to create a healthy and comfortable environment and reduce indoor contaminant concentration. An efficient design of HVAC system requires the proper placement of the supply and exhaust outlet with respect to a room's geometry configuration, distribution of indoor heat sources and indoor thermal conditions [1–3]. With the increase of the energy used for improving the quality of the indoor environment [4–6], there is a requirement to use effective ventilation strategies [7–9], while maintaining acceptable indoor thermal environment. In most air distribution systems, the ventilation performance and energy saving are greatly influenced by the arrangements of the supply, return and exhaust diffuser positions. Awad et al. [10] conducted experiments to investigate air flow patterns and velocity distribution using different exhaust diffuser locations. Their results indicated that the exhaust diffuser's position had a great impact on the level of the thermal stratification layers which consequently affected the cooling coil load. Cheng et al. [11] reported that a 20.8% of energy saving was achieved when the supply inlet located at the floor level and the return outlet located at occupied level. They also found that, the energy saving and indoor thermal comfort were improved by distributing the supply diffuser in the occupied zone. Bagheri and Gorton [12] investigated the relationship between the return outlet location and cooling load. They concluded that extra energy saving can be achieved by positioning the return vent in the cooled zone near the floor. Filler [13] reported that energy saving can be improved by placing the return vent near the perimeter walls of the room where the convective

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Nomenclature

Abbreviations

DV	displacement ventilation
HVAC	heating, ventilation and air conditioning system
IAQ	indoor air quality
PMV	predicted mean vote
PPD	predicted percentage of dissatisfied
STRAD	stratified air distribution system

Latin letters

C	the mean particle concentration (kg/m^3)
$C_{1\varepsilon}, C_{2\varepsilon}$	model constants in the term ε of the turbulence model
C_n	the normalised concentration
C_p	the contaminant concentration in a specific region (kg/m^3)
C_e	the concentration at exhaust (kg/m^3)
C_μ	model constant of the turbulence model
c_p	specific heat of air (J/(kg K)
d_p	particle diameter (m)
dt	particle residence time
F_D	inverse of relaxation time (s^{-1})
$\vec{F}_a$	force acting on particle (m/s^2)
$\vec{F}_b$	the Brownian force (m/s^2)
$\vec{F}_{thermal}$	the thermophoretic force (m/s^2)
$\vec{F}_s$	the Saffman's lift forces (m/s^2)
$\vec{g}$	gravitational acceleration (m/s^2)
i	trajectory index
j	cell index
k	turbulent kinetic energy per unit mass (J/kg)
$\dot{m}$	mass flow rate associated with each trajectory (kg/s)
$\dot{m}_e$	the exhaust mass flow rate (kg/s)
n	trajectory number
P_k	additional term in the turbulence model
$Q_{coil\text{-}STRAD}$	the cooling coil load for the STRAD system (W)
Q_{space}	the cooling coil load of space (W)
Q_{vent}	the ventilation load (W)
$Q_{coil\text{-}MV}$	the cooling coil load for the mixing ventilation system (W)
S	mean strain rate tensor magnitude
S_{ij}	strain rate tensor
T_e	the exhaust temperature (°C)
T_{set}	room set temperature (°C)
t	time (s)
$\vec{u}_p$	particle velocity vector (m/s)
u	fluid velocity (m/s)
u'_i	fluctuating velocity (m/s)
V_j	volume associated with i trajectory and cell j

Greek letters

β	coefficient of thermal expansion (1/K)
ε	turbulent dissipation rate (m^2/s^3)
λ	represents the molecular mean free path
μ	dynamic viscosity (kg/(m s)
ξ_i	the normally distributed random number
ρ	fluid density (kg/m^3)
ρ_p	particle density (kg/m^3)
σ_k	model constant for k equation of the turbulence model
σ_ε	model constant for ε equation of the turbulence model

heat flux will be extracted directly by means of the return vent before mixing with the air in the occupied zone. Hongtao et al. [14] found that extra energy saving can be achieved by separating the exhaust and return vent in two different elevations.

Thermal plumes generated from occupants and indoor heat sources play a significant role in increasing the exposure level for the occupants in the breathing zone by transporting the particles from floor level towards the upper part of the room, passing through the occupant inhaled area [15]. Therefore, the arrangement of the heat sources in a room may play an important role in the room's air flow pattern, thermal comfort, contaminant distribution and energy saving [16]. Park and Holland [17] investigated the effect of heat source positions on thermal stratification in a room served by a displacement ventilation (DV) system. They reported that indoor thermal environment and energy consumption are significantly influenced by changing the positions of the room's heat sources, and they also found that by increasing the height of heat source location the convective heat becomes less significant. Cheng et al. [18] performed the experimental and numerical study in a room chamber to investigate the influences of changing return opening on both thermal comfort and energy saving. In their experiments, the combination between the lamps and some exhaust opening was used. Further investigation of the combination between the lamps and exhaust opening was performed by the authors [19]. In this publication, the impact of the combination between the room lamps and exhaust opening on the energy saving was investigated numerically. The results showed that extra energy saving can be achieved in rooms that had combined the exhaust with lamps into one unit.

Safer thermal environmental conditions can be achieved in terms of contaminant distribution when using the exhaust vent at the upper part and the supply diffuser at the low part of the room [20]. The influences of the supply and exhaust locations of diffusers were numerically investigated by Khan et al. [21]. Their results showed that a better indoor air quality (IAQ) was achieved by locating the exhaust opening near the ceiling level. Kuo and Chung [22] investigated the impact of supply and outlet diffuser positions on indoor thermal comfort in the occupied zone using different ventilation strategies. Based on their simulation results, they found that the longer the supply air throw in the occupied region is, the better the indoor thermal comfort achieved. He et al. [1] reported that the exhaust vent position may not greatly influence the pattern of airflow, but it can significantly affect the indoor exposure level. Lin et al. [23] studied the impact of the position of the supply diffusers on the DV system performance. They revealed that for a better indoor environment the supply opening should be located close to the room centre.

Most previous studies have investigated the effect of the supply and return diffuser's locations on the performance of a ventilation system, thermal comfort, IAQ and energy saving. But limited research has been performed to investigate the relationship between the location of the exhaust outlet diffuser and the heat sources in a room. The thermal plumes of the indoor heat source and the exhaust temperature play a significant role in indoor contaminant transport and energy saving respectively [13,24]. In this study, a validated CFD model was used to investigate the effect of different locations of the exhaust diffuser, as well as the combination of heat sources and exhaust outlet on indoor thermal comfort, vertical temperature difference, contaminant concentration distribution in the breathing zone, quality of inhaled air and energy saving. For the indoor environment, there are many sources of the pollution and some of them are generated by heat sources and human activity while the others come from outdoor surrounding [25,26]. Generally, most indoor contaminants in an office arise

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