A Performance Comparison of Three Ventilation Modes in an Office with Internal Partitions

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Abstract Partitions are widely installed in commercial buildings, which could block the supplied air and then have an influence on indoor environment. This paper mainly aims to investigate the performances of mixing ventilation (MV), displacement ventilation (DV), and stratum ventilation (SV) in a partitioned office via computational fluid dynamics (CFD). A simulation model was established and validated through experimental measurement. The distributions of temperature and carbon dioxide (CO_2) concentration, predicted mean vote index (PMV), and local mean age of air were examined. The results indicated that the partition had significant effects on ventilation performances under DV, wherein the obstacle effect of the partition could lead to both heat and contaminant accumulations around the occupant, and then resulted in a risk of thermal discomfort as well as a reduction of inhaled air quality. In contrary to DV, the indoor air quality and thermal comfort of occupant were slightly influenced by the partition under MV and SV. With the same air change rate and supply air temperature, SV exhibited a better cooling effect and ensured a higher inhaled air quality than MV and DV in a partitioned office. The results of this study could help to provide a reference for the design of the air-conditioning system in a space with partition.

Keywords Internal partition · Air distribution · Thermal comfort · Indoor air quality (IAQ) · Air age

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1 Introduction

Recent studies have shown that people spend nearly two-thirds of their time in buildings and the proportion could be even up to 90% for urban citizens [1]. Indoor thermal comfort and air quality have been especially significant for people's health and work efficiency [2, 3].

Heating, ventilation, and air conditioning (HVAC) system is an effective measure to improve indoor environment. It introduces air which has been handled into rooms to adjust temperature or dilute contaminants and has become a vital component in modern buildings [4]. It is also recognized that HVAC systems represent 20– 40% of the total building energy consumption [5]. Thus, there could be a contradiction between the need to improve indoor environment and the need to reduce energy usage in buildings [6]. An ideal design of HVAC system should be able to provide better thermal comfort and air quality with lower energy consumption.

Considering the indoor airflow, even though the design of HVAC system has taken account of the airflow in an empty space in advance, the air movement could still be affected by final user layouts, such as space shape, internal heat sources, and obstructions. In a ventilated space, obstructions could take the forms of decoration, furniture, and partition, etc., blocking the supplied air and subsequently change the indoor airflow pattern, which generally has an impact on the ventilation performance [7, 8].

This paper aims to investigate the performances of MV, DV, and SV in a partitioned office. The results could provide a reference for the practical engineering design of the air-conditioning system.

2 Methodology

2.1 Experimental Arrangement

The experiment was carried out in a test chamber, with the dimensions of 3.75 m (length) × 2.85 m (width) × 2.6 m (height), as shown in Fig. 1. Under SV and DV, the air was supplied from a 0.20 m × 0.17 m air grille and three 0.25 m × 0.25 m air grilles, respectively, and discharged through a 0.6 m × 0.6 m perforated ceiling exhaust. The effective area ratio of the perforated exhaust was 15.3%. Under MV, the air was supplied from a top inlet and exhausted via a bottom outlet, both with a dimension of 0.20 m × 0.17 m. A 0.25 m × 0.4 m × 1.2 m box, heated by three 25 W light bulbs, was used to simulate a sedentary occupant in the test chamber. Two 72 W fluorescent lights were mounted on the ceiling. A partition was installed in front of the occupant, with a height of 1.1 m and a thickness of 0.02 m. The ventilation rate was calibrated to be 5 air changes per hour (ACH) while the supply air temperature was 21 °C. The humidity was not taken into account in this work since the previous research had shown that within a range of 30–70%, the humidity has an insignificant effect on occupant's thermal comfort [9].

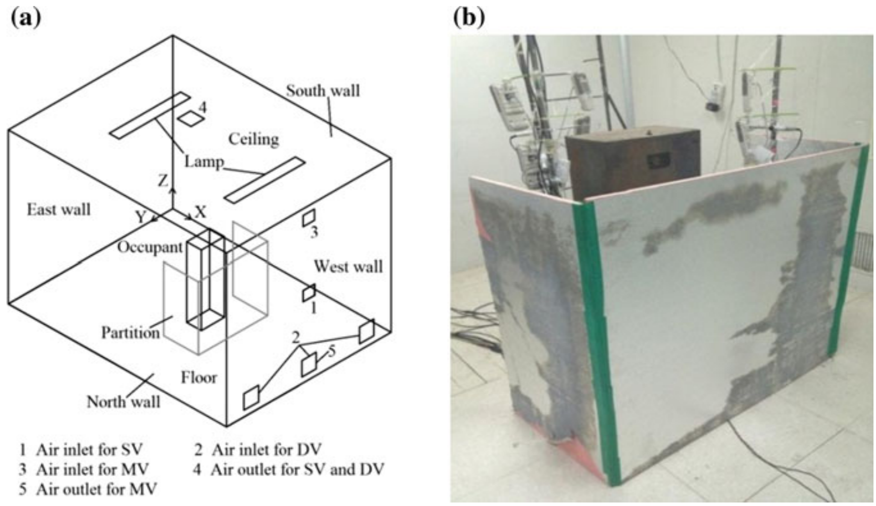

Fig. 1 Diagram of experiment. **a** Configuration of test chamber. **b** Photo of test instruments

CO_2 gas was released from a hole at 1.1 m height on the front side of the manikin, with a flow rate of 320 ml/min. The temperature of CO_2 gas was controlled at 36 °C, to simulate the respiration effect of the occupant. The envelope of the test chamber was constructed by 75 mm steel sandwich sheet, which used foam insulation material as the sandwich.

The SWEMA hot-wire anemometer system was adopted to measure air velocity and temperature. For velocity, the measuring range is 0.05 m/s to 3 m/s, with the measuring error of ±0.03 m/s for 0.05 m/s to 1.00 m/s and 3% of readings for 1.00 m/s to 3.00 m/s. The measuring range for temperature is 10–40 °C, and the measuring error is ±0.3 °C.

Nine plumb lines were arranged in the test chamber as shown in Fig. 2. Along each plumb line, the velocity and air temperature on the height of 0.4, 1.2, and 1.9 m were recorded during the experiment.

2.2 Numerical Model and Boundary Condition

Commercial program Fluent was used to perform the analysis in this paper. The employed turbulence model was RNG $k - \varepsilon$ model. The equations of the model were discretized into algebraic equations by the second-order upwind scheme. The SIMPLE algorithm was used to solve the coupled velocity and pressure. The air inlet was defined as an opening with uniform airflow velocity. The outlet boundary conditions were set as outflow of room air. The discrete ordinates (DO) radiation model was adopted to simulate the radiation of walls. The stand wall

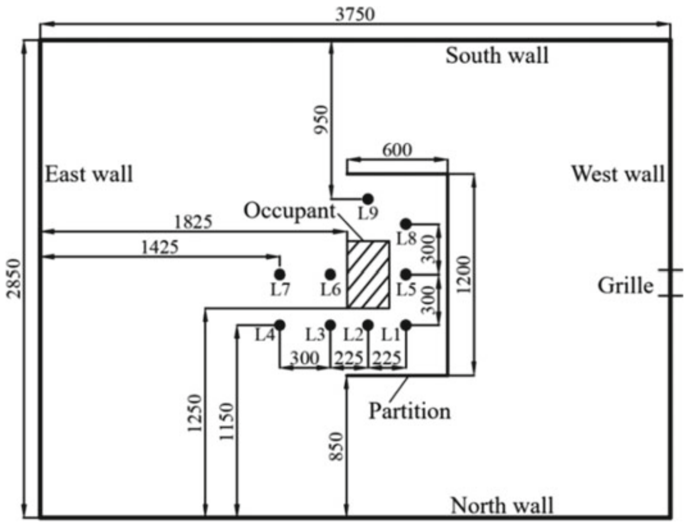

Fig. 2 Plan view of measuring points

Table 1 Boundary conditions (BC)

Number	Name	Temperature BC	Velocity BC
1	Occupant	Constant heat flux	–
2	Partition	Adiabatic	–
3	Lamp	Constant heat flux	–
4	Inlet	Constant temperature	Uniform velocity
5	Outlet	–	Local unidirectional
6	Wall	Adiabatic	–

function was used to describe the turbulent flow properties in the near-wall region. The wall surfaces were set as adiabatic. Detailed boundary conditions were listed in Table 1.

In this study, the performances of MV, DV, and SV in a partitioned office were evaluated and compared via the above-mentioned model. The supplied air temperature was set to be 21 °C and the ventilation rate was 5 ACH.

2.3 Evaluation Criteria of Thermal Comfort and IAQ

Mean age of air. The mean age of air is defined as the averaged time for all air molecules to travel from the supply diffuser to that particular point. It represents the ability to remove contaminant in a ventilated room. The younger the mean age of air, the stronger ability the ventilation system has to remove contaminant [10].

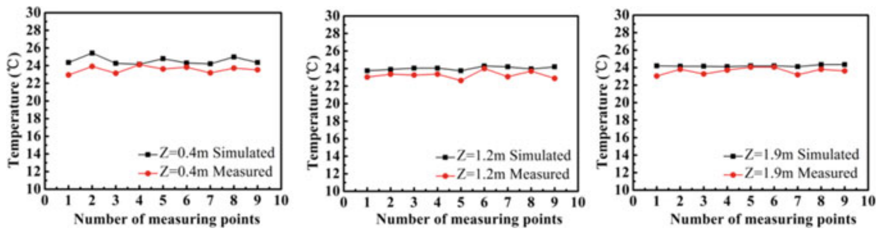

Fig. 3 Comparison of measured and simulated temperatures

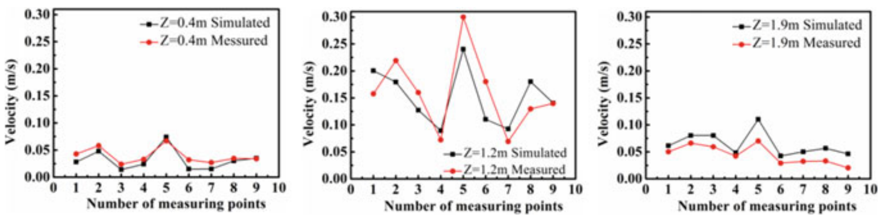

Fig. 4 Comparison of measured and simulated velocities

PMV index. This paper utilized PMV as the evaluation criteria of thermal comfort. In this study, the occupant was sedentary, thus a metabolic rate of 1 met (58 W/m^2) was adopted. The clothing insulation factor was 0.6 clo (1 clo = 0.155 m^2 K/W) that corresponds to summer dressing and the relative humidity was 50%.

2.4 Validation of the CFD Model

The comparison of the measured and simulated results for temperature and velocity were shown in Figs. 3 and 4. In Figs. 3 and 4, both the simulated and experimental results exhibited the reverse distribution characteristics of temperature under SV, i.e., with relatively higher air velocity and relatively lower temperature at the breathing level (about the height of 1.1 m). From Figs. 3 and 4 it could be found that the discrepancies between the measured and the simulated results were within acceptable range.

3 Results and Discussions

3.1 Distributions of Temperature and CO_2 Concentration

Figure 5 displayed the simulated temperature fields under three ventilation modes. The temperature around the occupant under MV, DV and SV were 26 °C, 24 °C, and 24 °C, respectively. It was illustrated that with the same supply air temperature and airflow rate, DV and SV had a higher cooling performance than MV for the occupant in a partitioned environment.

Furthermore, under SV (Fig. 5c), the air temperature gradient in front of the occupant was reverse distributed, i.e. with a lower temperature at the breathing level (1.1 m height) and a higher temperature at the ankle level (0.1 m height), while that under MV was uniform distributed (Fig. 5a). It indicated that for SV and MV, the characteristics of temperature distribution could remain the same although in a space with partition. However, under DV (Fig. 5b), the temperature profile inside and outside the partition were markedly different, wherein an obvious vertical temperature gradient formed outside rather than inside the partition. This was attributed to the block effect of the partition, which prevented the cool supply air flowing directly towards the occupant and reduced the temperature gradient in the partition. These results suggested that in comparison with MV and SV, the partition under DV had a significant effect on temperature profile in front of the occupant.

The CO_2 concentration fields under three ventilation modes were shown in Fig. 6. It demonstrated that the CO_2 concentration in the breathing zone of occupant under MV was lower than that under DV and SV. Significant subsidence and accumulation of CO_2 could be found in Fig. 6b, c. This was because under MV, the supply air was delivered and descended from the upper zone of the room, and then the partition had a negligible effect on the air diffusion in the occupied zone. Thus the contaminant in front of the occupant could be effectively diluted. On the contrary, under DV and SV, the partition was against the main air stream, which made it difficult to remove the contaminant in an efficient way, finally resulted in a higher concentration of CO_2 inside the partition. However, under SV, the CO_2 only trapped at the bottom area, which had slight effect on the quality of inhaled air for occupant.

Figure 7 showed the air age distribution for different cases. It could be seen that among the three ventilation modes, the highest air age in the breathing zone of occupant occurred under MV (Fig. 7a), with a value of 700 s, followed by DV (Fig. 7b) and SV (Fig. 7c), with values of 414 s and 357 s, respectively. Under DV, the cool air was supplied from the bottom of the room and driven upward by the thermal buoyancy. For the area outside the partition, the existence of the partition reduced the heat transferred from internal heat source, which weakened the buoyant force and enlarged the air age difference along the vertical direction. On the other hand, the heat accumulation inside the partition promoted the mixing of the air near the occupant, decreasing the difference of air age inside the partition.

3.2 Values of Air Age and PMV

The values of PMV index under three ventilation modes were displayed in Fig. 8, in which the PMV values around the occupant under MV (Fig. 8a) and DV (Fig. 8b) were clearly higher than that under SV (Fig. 8c). Under MV, the PMV

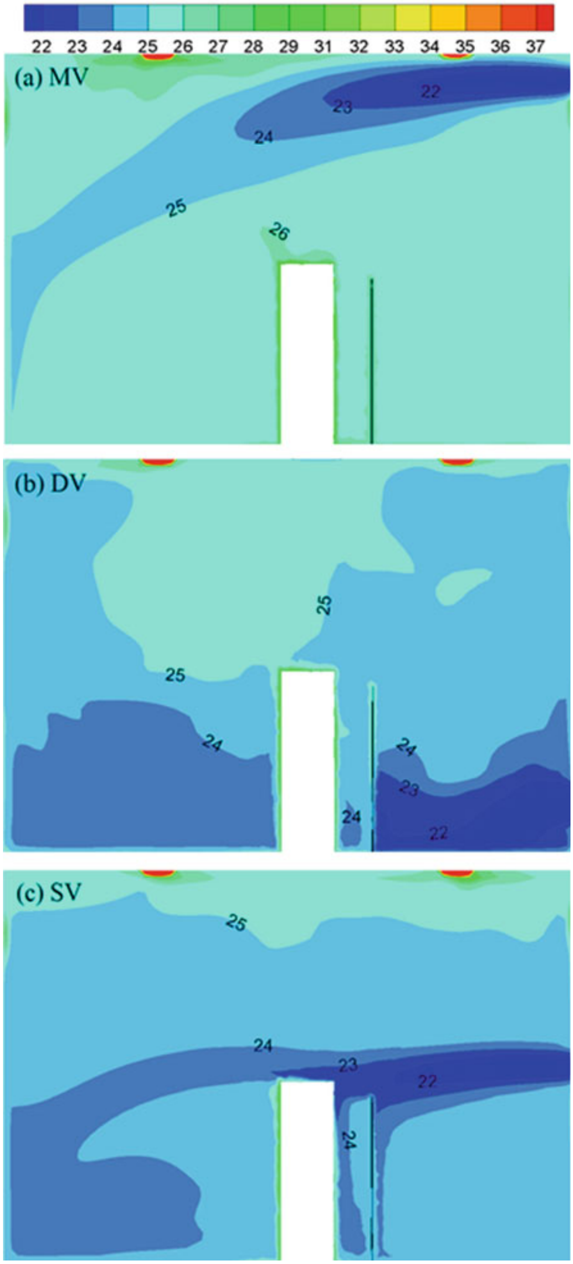

Fig. 5 Temperature distribution at section $Y = 1.4$ m (°C). **a** MV. **b** DV. **c** SV

value around the occupant was about 0.6, and it was slightly affected by the partition. Under DV, the PMV value inside the partition was higher than that outside the partition. This was mainly ascribed to the heat accumulation caused by the obstacle effect of the partition. In addition, under MV and DV, the PMV values

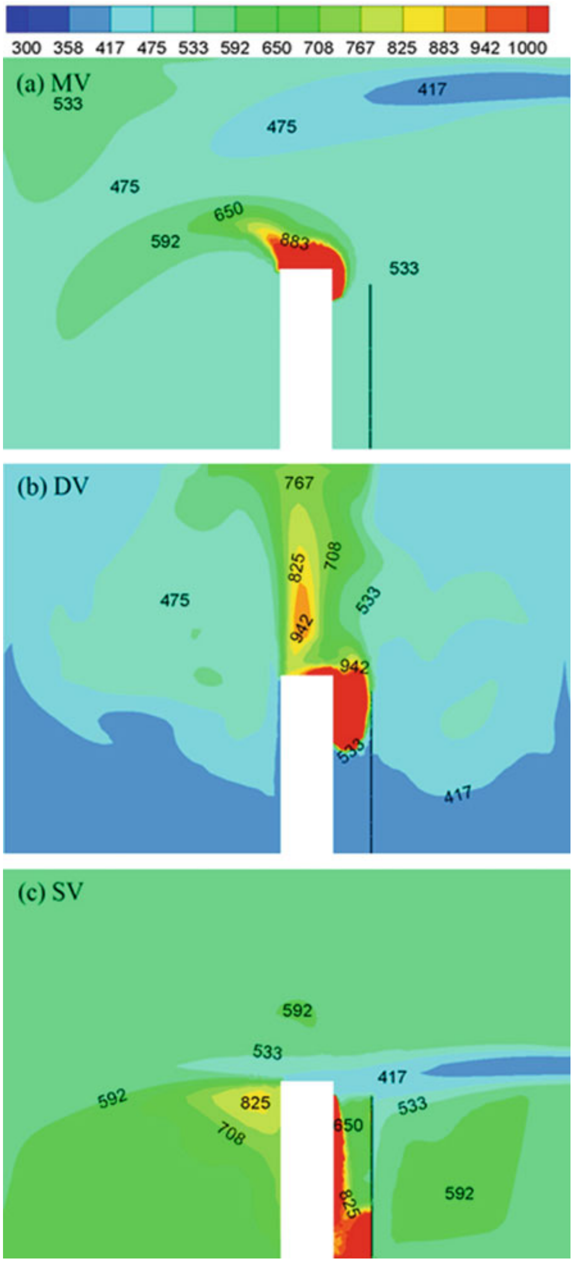

Fig. 6 CO_2 concentration at section Y = 1.4 m (ppm). **a** MV. **b** DV. **c** SV

near the occupant were already close to the upper limit of the comfort zone according to ISO 7730 (with an upper bound value of 0.7), which may result in a hot sensation for the occupant. Under SV, the PMV value in front of occupant was around −0.6, which indicated that with the same supply air temperature and flow

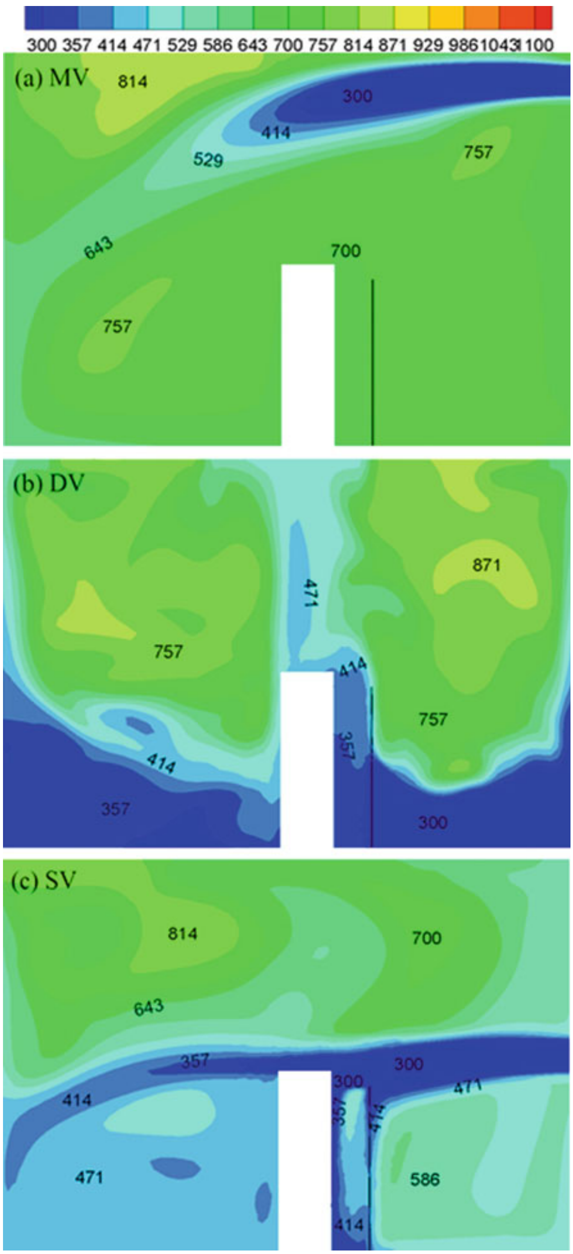

Fig. 7 Distribution of air age at section Y = 1.4 m (s). **a** MV. **b** DV. **c** SV

rate, SV exhibited the highest cooling performance for occupant in comparison with MV and DV. It also manifested that SV had the potential to provide a satisfactory thermal comfort for occupant in a partitioned office with higher room temperature setting or higher intensity heat source.

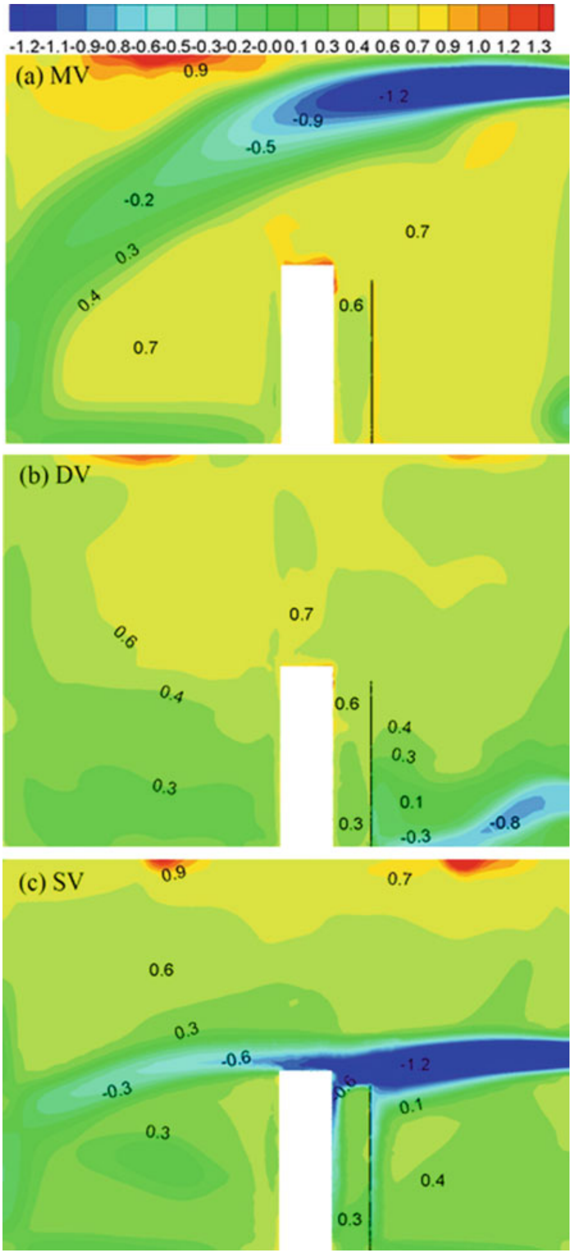

Fig. 8 PMV index at section Y = 1.4 m. **a** MV. **b** DV. **c** SV

4 Conclusions

This study examined the effect of the partition on performances of MV, DV, and SV. The main conclusions are as follows:

1. Under DV, the partition had significant effects on PMV values as well as distributions of temperature, CO_2 concentration, and air age. Due to the block effect, the partition could cause accumulations of heat and contaminant near the occupant, resulting in a low-quality inhaled air and a risk of thermal discomfort for the occupant.
2. Under MV and SV, the inhaled air quality and thermal comfort of occupant were slightly influenced by the partition. Compared with MV and DV, when the supply air temperature and air change rate keep the same, SV could provide a higher indoor air quality and achieve a better cooling performance for the occupant.

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