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Performance Comparison of Upward and Downward Ventilations

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ABSTRACT

The performance of upward and downward ventilations was compared under various conditions. Occupants were simulated by heated dummies. Carbon dioxide was released beside them. The experiments indicated that the distribution of ventilation objects in a space was influenced significantly by the free convection caused by its occupants and by the temperature of room air. The room air temperature have to be lower than 27°C to have a good relative ventilation efficiency in the breathing zone in the upward ventilation. The upward ventilation extracted CO_2 more efficiently than the downward ventilation at the transient condition, due to the upward free convection caused by the metabolic heat around a human body. In such a room as a classroom, where occupancy and evacuation are repeated in a short time, the relative ventilation efficiency in the breathing zone was found to be able to be kept higher than 100 %.

KEYWORDS Ventilation Efficiency, Air Distribution, Model Experiment

INTRODUCTION

In the study of displacement ventilation by Sandberg and Lindstrom (1987), the calculated height of the "front," which is the horizontal border between the clean and contaminated zones, was 0.2 to 0.3 m higher than the theoretical height where the volumetric flow rate of the plume above the heat source becomes equal to the ventilation airflow rate. The required minimum ventilation rate to keep the stratification level higher than 0.8 m with a slender cylindrical heat source of 600 W and a tracer gas source at floor level was 52.5 L/s (Heiselberg and Sandberg 1990).

Cox et al. (1990) reported that there was no improvement of ventilation efficiency in the breathing zone with a displacement ventilation system compared to a dilution ventilation system. Sandberg and Blomqvist (1989) pointed out that there were limits to that type of ventilation. They also noted that the concentration in the breathing zone, with the flow rates normally supplied to office rooms, was the same as with traditional mixing systems. In these two studies, a 100 W electric bulb was used for a simulation of a person, which caused an upward free convection. But the convective heat dissipation of a human body is about 30 W, and the shape of a plume of a point heat source is different from that of a human body heat source.

In rooms for sedentary occupancy, the main ventilation objective is the removal of pollutants produced by the occupants. The free convection around an occupant caused by its metabolic heat plays an important role in the ventilation process, especially in well-insulated and airtight buildings, where the proper room air movement is reduced. Distribution of occupant-produced CO_2 must be examined and understood carefully to be included in indoor environmental design, because it is transported by both the free convection around the occupants and at wall surfaces and the ventilation airstreams. In this study, improvement of the pollutant extraction effect is investigated through experiments of upward ventilation and downward ventilation using heated dummies and by comparing various experimental conditions.

EXPERIMENTAL PROCEDURE

Heated Dummy

The used heated dummy has a shape of cylinder, a tall of 1.28 m, and a surface of 1.73 m^2 (Figure 1). It is made with galvanized iron plate spiral duct. The heat generation was controlled by power supply to the lamp installed in the cylinder according to the conditions in the experimental space. Carbon dioxide was released at the position, which corresponds to the mouth of an occupant, from a CO_2 cylinder.

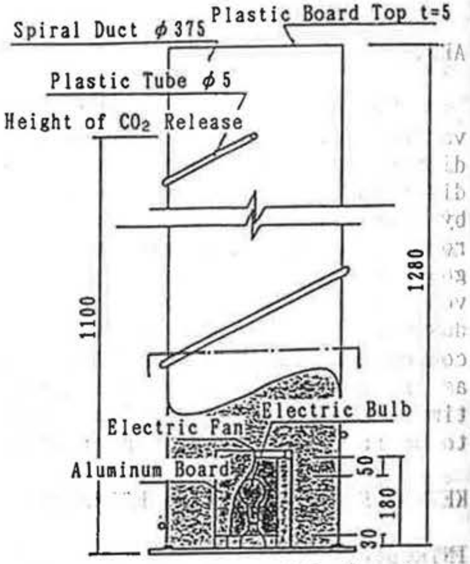


Figure 1 Side View and Inside of Heated dummy (Unit: mm)

Space of Experiment

In a large, well-insulated laboratory, a small experimental enclosure of a floor area of 10.7 m^2 (3.140 m by 3.395 m), a height of 3.396 m, and a volume of 36.2 m^3 was installed (Figure 2). The positions of an inlet and an outlet of the ventilation air were exchangeable at the upper and the lower parts of the enclosure. The supply and extract airs were forced into and from the room by fans. These two airflows were adjusted to be equal to balance the pressure inside the space with the outside.

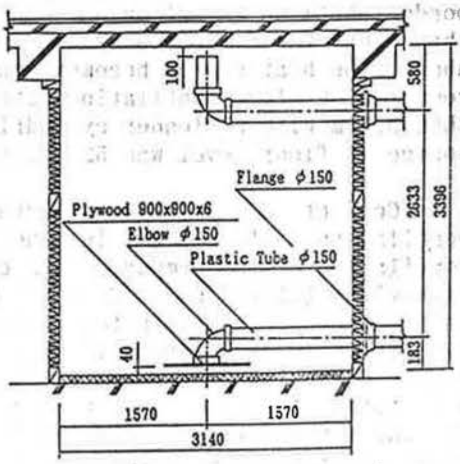


Figure 2 Vertical Section of Experimental space (Unit: mm)

Measuring Methods

The floor plan was divided into two triangles by a diagonal line. The two sampling points for CO_2 and temperature were located at the centroids of the two triangles. At each of the locations, seven

Table 1
Experimental Conditions
Totally fifty-four experiments were carried out according to the combinations of the following conditions.

Ventilation Direction	Dummy Number	Ventilation Rate per Dummy (m^3/h)	Temp. Difference between Dummy Surface & Room Air (°C)
Upward Downward	2	7	4
	4	14	8
	6	21	12

measurement points were distributed vertically at 200 mm, 600 mm, 1,100 mm, 1,600 mm, 2,100 mm, 2,600 mm, and 3,100 mm above the floor. The CO_2 concentration and the temperature of supply, extract, and outdoor air were measured. Dummy surface temperature was also measured at four points. The measurement was repeated at an interval of three minutes. Infrared absorption-type concentration meters and copper-constantan thermocouples were used for the measurement.

The convective heat of the dummies was controlled considering the aiming temperature difference between the room air and the dummy surface, the radiative heat loss of the dummies and airstream caused by ventilated air, which depended on the ventilation types and ventilation rates.

When the room reached a thermally steady condition, an experiment started without CO_2 released. Thirty minutes later, CO_2 release was started and continued for 120 minutes. The measurement continued for 30 minutes after the stop of CO_2 release. Fifty-four experiments were carried out with various combinations of the ventilation type, dummy number, ventilation rate per dummy, and temperature difference between the dummy surface and the room air. The conditions are shown in Table 1.

EXPERIMENTAL RESULTS

Influence of Temperature difference

Figure 3 shows the vertical CO_2 distribution after the duration of one air change. In the upward ventilation when the temperature difference between the dummy surface and the room air was 8°C or 12°C, CO_2 concentration was low in the lower part than at a height of about 1 m from the floor. The CO_2 concentration was relatively high and almost constant above this height in the upward ventilation. While, CO_2 concentration at the upper part was almost the same as that at the lower part in the downward ventilation. The average CO_2 concentration in the occupied zone in the upward ventilation was much lower than that in the downward ventilation. When the temperature difference was 4°C, the CO_2 was scarcely transported to the upper part by free convection. It was diffused or descended to the

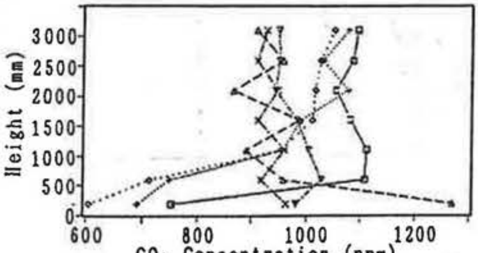


Figure 3 Vertical CO₂ distribution at the time of one air change

lower part. The CO_2 transportation effect at the temperature difference of about 4°C or at the room air temperature of 27°C seemed not match with that of the higher temperature differences.

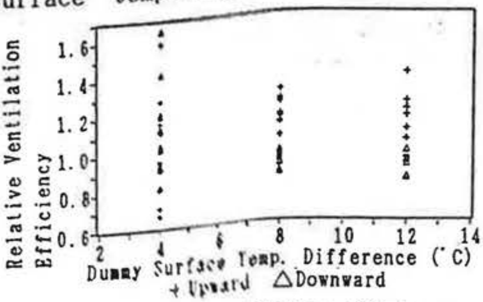
In the transient condition, an absolute ventilation efficiency, E^a, and a relative ventilation efficiency in a breathing zone, E^r, are defined as

$$E^a = Q\int Ce(T)dT/\{mT+Q\int Cs(T)dT\} \quad (1)$$
$$E^r = \int\{Ce(T)-Cs(T)\}dT/\int\{Cb(T)-Cs(T)\}dT \quad (2)$$

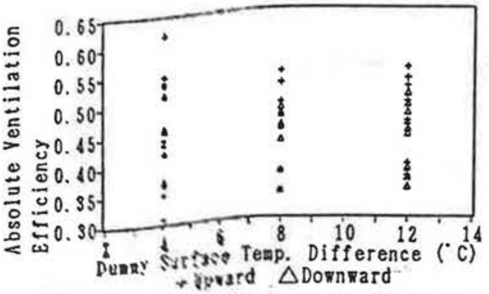
where

Q = ventilation rate, L/min,
$Ce(T)$ = CO_2 concentration of extract air at time T, L/L,
$Cs(T)$ = CO_2 concentration of supply air at time T, L/L,
$Cb(T)$ = CO_2 concentration in the breathing zone at time T, L/L,
m = CO_2 production rate, L/min,
T = time, minute.

The authors wish to distinguish the difference in CO_2 concentration between extract air and it in the breathing zone by relative ventilation efficiency conceptually. The influence of temperature difference on absolute ventilation efficiency and relative ventilation efficiency in the breathing zone at the time of one air change are shown in Figure 4. When the dummy surface temperature difference was 4°C, there is no difference in ventilation efficiencies. While, ventilation efficiencies of upward ventilation was higher than those of downward ventilation when the dummy surface temperature differences was higher. This tendency also shows the

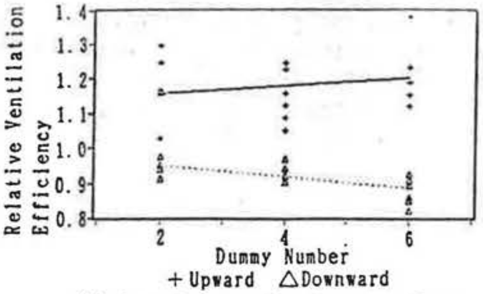


(a) Relative ventilation efficiency in the breathing zone

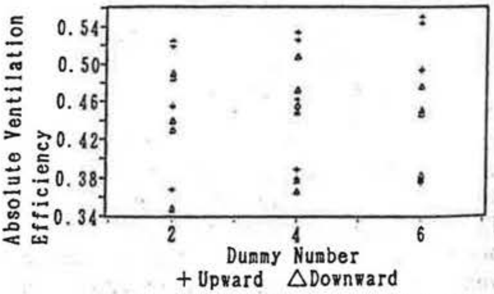


(b) Absolute ventilation efficiency

Figure 4 Influence of temperature difference on ventilation efficiencies at the time of one air change



(a) Relative ventilation efficiency in the breathing zone



(b) Absolute ventilation efficiency

Figure 5 Influence of dummy number on ventilation efficiencies at the time of one air change discontinuity in temperature difference on CO_2 transportation effect. The results of dummy surface temperature difference of 4°C are excluded in the following analysis because the free convection was not clear.

Influence of Dummy Number

The influences of dummy number on absolute ventilation efficiency and relative ventilation efficiency in the breathing zone at a time of one air change are shown in Figure 5. When dummy number increased, the amount of free convection also increased, and stratificational effect became clear; i.e., the CO_2 concentration becomes high at the upper part of the room. Consequently, the relative ventilation efficiency in the breathing zone increased with upward ventilation and decreases with downward ventilation.

The absolute ventilation efficiency approached unity when the room air reached a steady condition. When dummy number increased, the time to reach a steady condition became short. Consequently, the absolute ventilation efficiency increased.

Comparison of Experimental Results with the Assumption of Complete Mixing

The effective ventilation rate was calculated from the concentration decay after the CO_2 release stopped. The following is the equation for calculation of the ventilation rate from a decay of tracer gas concentration in a well-mixed room.

$$Q' = V / t \times \ln\{(C_1 - C_o) / (C_t - C_o)\} \tag{3}$$

where

Q' = effective ventilation rate, L/min,
V = volume of room, L,
t = elapsed time, minute,
C_1 = CO_2 concentration in room at initial measurement, L/L,
C_t = CO_2 concentration in room at final measurement, L/L,
C_o = CO_2 concentration in supply air, L/L.

The effective ventilation rate is a theoretical quantity, not a physical flow rate. It can be greater than or less than the real ventilation rate. When complete mixing occurs, it becomes equal to the real ventilation rate. The arithmetic mean of concentrations of all measuring points was applied for the CO_2 concentration in the room air. The time interval was 30 minutes after CO_2 release stopped. The upward and downward ventilation respectively extracted 1.26 and 1.23 times more CO_2 than a well-mixed ventilation in this study. When a room is ventilated using the directed airstream, CO_2 can be extracted more effectively than in the well-mixed condition. It is possible to heighten ventilation efficiency and to lessen the ventilation rate requirement by using the directional stream.

Timely Variation of Relative Ventilation Efficiency

Timely variations of the relative ventilation efficiency in the breathing zone are shown in Figure 6. The relative ventilation efficiencies were larger than unity and decreased slightly with the lapse of time in the case of upward ventilation, while relative ventilation efficiencies were smaller than unity and increased with the lapse of time in the case of downward ventilation. In the upward ventilation, the lower level of the high concentration zone descended with the lapse of time and the breathing zone was included in the upper contaminated zone. So the CO_2 concentration in the breathing zone became equal to that of well-mixed condition. In the case of downward ventilation, the room air approached to well-mixed condition with the lapse of time because of the concurrent of upward free convection caused by occupants' heat dissipation and downward airstream by ventilated air. The upward ventilation was not more effective than well-mixed condition in the steady condition, but effective in the initial transient condition.

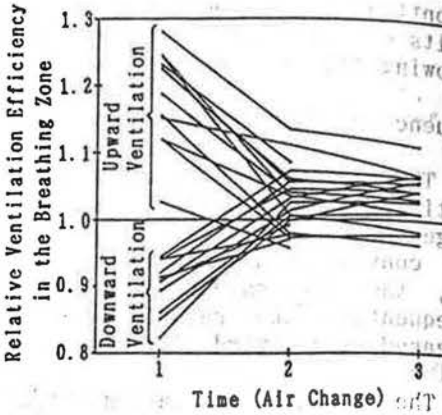


Figure 6 Timely variations of relative ventilation efficiency

CONCLUSION

The experiments indicated that the distribution of ventilation objects in the space was influenced significantly by the free convection caused by its occupants and by the temperature of room air. As an upward displacement ventilation system utilizes vertical CO_2 concentration differences by buoyancy force, the temperature conditions of the room play an important role. The room air temperature have to be lower than 27°C to transport the occupant-produced CO_2 to upper part of the room effectively.

Upward ventilation extracted CO_2 more efficiently than downward ventilation during the initial transient condition, due to the upward free convection caused by the metabolic heat around a human body. But the merit of upward ventilation decreased as time passed. In rooms such as a classroom, where occupancy and evacuation are repeated in a short period, the relative ventilation efficiency in the breathing zone was found to be able to be kept higher than 100 %.

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