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POSSIBILITY FOR INCREASING VENTILATION EFFICIENCY WITH UPWARD VENTILATION

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ABSTRACT

A ventilation method to attain an improved indoor air quality with effective use of energy was examined in a small, office-type experimental space. The experiments were carried out using human subjects. The positions of air supply and extract openings were exchangeable in the space, and initial room air temperature and supply air temperature were controlled. This paper reports the possibilities of ventilation efficiency improvement and lessening of ventilation requirements by upward ventilation at various temperature conditions. The results indicated that with upward ventilation, if the occupant is the only contaminant source, the ventilation requirement could be lessened to about 11.8 cfm (5.6 L/s) per person without exceeding a CO_2 concentration of 1,000 ppm in the breathing zone because the change of room CO_2 content due to variation of the ventilation rate is influenced less by an upward ventilation system than by a traditional mixing system. The supply air temperature must not be higher than the room air temperature to keep the CO_2 concentration in the breathing zone low.

INTRODUCTION

The basic purpose of ventilation is to create a healthy air quality indoors. The effective use of energy is also an important consideration. Generally, the former is emphasized over the latter. A method that realizes good air quality with effective use of energy is the subject of this study.

Lewis et al. (1969) observed free convection around bodies using a schlieren photographic system and measured air velocity in free convection with a hot wire anemometer. Free convection was strong enough to transport floating particles from near the floor to the nasal orifice. Yaglou et al. (1936) defined the effective air supply as the airflow that passed over the occupied zone and therefore removed the products of respiration and transpiration.

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 0.06 to 0.09 ft (0.2 to 0.3 m) higher than the theoretical height where the volumetric flow rate of the plume above the heat source became equal to the supply ventilation airflow rate. The required minimum ventilation rate to keep the stratification level higher than 5.9 ft (1.8 m) with a slender cylindrical heat source of 600 W and a tracer gas source at floor level was 111.2 cfm (52.5 L/s) (Heiselberg and Sanberg 1990).

The air velocity in the free convection plume above a sitting body was reported to be 30 fpm (0.15 m/s) by Katz (1972). Daws (1970) reported that the volume flow rate was calculated to be about 70 cfm (33 L/s) at a height of 5.5 ft (1.68 m) above a point heat source of 100 Btu/h (29 W), which corresponds to the convective heat dissipation of a human body, and the resulting convection stream was surprisingly strong although that was a weak heat source. In Homma and Yakiyama's (1988) measurements, the volume flow rate was 85 cfm (40 L/s) for a sitting body in a long-sleeved shirt, and it was 87 cfm (41 L/s) for a sitting body in an undershirt at a height of 6 ft, 8 in. (2.0 m) above the floor. The plume flow above an occupant is several times larger than the fresh air requirement for body odor, which is 15 cfm (7.5 L/s) for a person (ASHRAE 1989).

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 341 Btu/h (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 102 Btu/h (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, such as classrooms, offices, and computer rooms, the main ventilation objective is removal of pollutants produced by the occupants. The free convection around a human body caused by metabolic heat starts to play an important role in the ventilation process, especially in well-insulated and airtight buildings, where air movement is reduced. Distribution of occupant-produced CO_2, which is transported by both the free convection and ventilation airstreams, must be carefully examined and understood to be included in indoor environmental design. In this study,

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improvement of the extraction effect is investigated by upward ventilation compared to downward ventilation through experiments using human subjects and by comparing various thermal conditions.

EXPERIMENTAL PROCEDURE

Space of Experiment

Inside a large, well-insulated laboratory, a small experimental space was installed that had a floor area of 116.4 ft^2 (10.3 ft by 11.3 ft [10.8 m^2, 3.140 m by 3.440 m]), a height of 11.3 ft (3,443 m), and a volume of 1313.4 ft^3 (37.2 m^3). Figure 1 shows the plan and the cross section of the experimental space. The walls, ceiling, and floor were well insulated. All cracks were caulked. The positions of the inlet and the outlet of the ventilation system were exchangeable at the upper and lower parts of the room. The supply and extract air are forced into and from the room by fans. These two airflows are adjusted to be equal. The inside pressure of the space was balanced with the outside pressure.

Subjects

Persons of normal Japanese physique were chosen from among university students as subjects. In each experiment series, the same subjects attended to keep metabolic heat and CO_2 production constant. During the experiments, subjects were performing light work or reading books.

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 measurement points were distributed vertically at 0.7 ft (200 mm), 2.0 ft (600 mm), 3.6 ft (1,100 mm), 5.2 ft (1,600 mm), 6.9 ft (2,100 mm), 8.5 ft (2,600 mm), and 10.2 ft (3,100 mm) above the floor. The height of 3.6 ft (1.1 m) corresponds to the height of the breathing zone of a sedentary subject. For the measurement of CO_2 concentration, three concentration meters were used. The sampling points were connected to the concentration meters with plastic tubes having a diameter of 0.24 in. (6 mm). A solenoid valve was attached to the end of each of the sampling tubes. The air from all the sampling points was passed to the concentration meter alternatively by controlling the solenoid valves. The concentration of supply, extract, and outdoor air was also measured. Each concentration measurement took 20 seconds; the total measuring time for the 18 sampling points was 120 seconds. Copper-constantan thermocouples were used for the temperature measurement. The measurement of concentration and temperature was repeated at an interval of three minutes. Infrared absorption-type concentration meters were used.

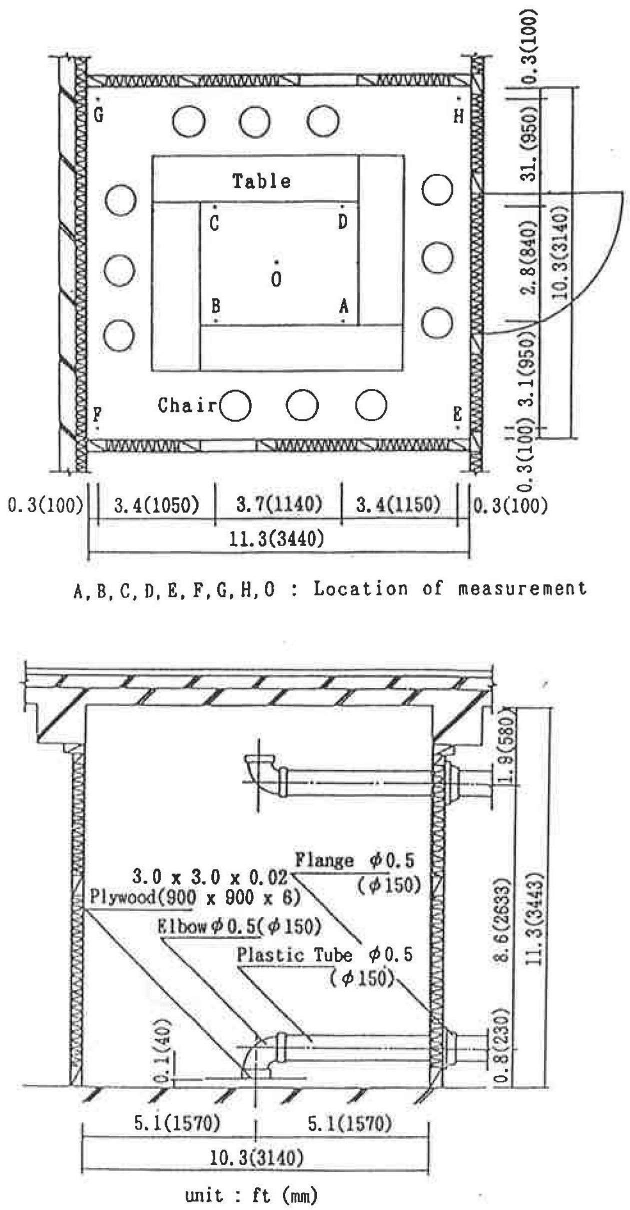

Figure 1 *Floor plan and vertical section of experimental space and locations of measuring points.*

When the room reached a thermally steady condition, an experiment started without subjects. Thirty minutes later, the subjects entered the room and stayed there for 60 minutes in the earlier ten experiments and for 120 minutes in the latter eight experiments. The measurement continued for 30 minutes, even after the subjects left the room. The conditions of each experiment are shown in Table 1.

The airflow rates of the center of the supply and extract ducts were controlled to get the same value so as

TABLE 1

Experimental Conditions and Relative Ventilation Efficiency in the Breathing Zone at the End of Occupancy

EXP. No.	Vent. Rate cfm (L/s)	Ventilation Type	Temperature F (℃)					CO$_2$ Concentration ppm							<E^r>
			Supply Air	Extract Air	Avg. Room Air	(Ext. Air) - (Sup. Air)	(Room Air) - (Sup. Air)	Supply Air	Extract Air	Room Avg.	Breathing Zone	(Ext.) - (Sup.)	(Room) - (Sup.)	(Breath. Zone) - (Sup.)	
2001	23.5 (11.1)	Upward	74.1 (23.4)	76.1 (24.5)	75.0 (23.9)	2.0 (1.1)	0.9 (0.5)	484	952	946	995	468	462	511	-
2002	29.4 (13.9)		70.0 (21.1)	70.9 (21.6)	70.5 (21.4)	0.9 (0.5)	0.5 (0.3)	494	959	927	933	465	433	439	-
2003	35.3 (16.7)		70.5 (21.4)	70.9 (21.6)	70.0 (21.1)	0.4 (0.2)	-0.5 (-0.3)	460	902	852	873	442	392	413	-
2004	41.2 (19.4)		69.8 (21.0)	70.0 (21.1)	69.4 (20.8)	0.2 (0.1)	-0.4 (-0.2)	446	827	814	809	381	368	363	-
2005	47.1 (22.2)		70.3 (21.3)	71.1 (21.7)	70.5 (21.4)	0.8 (0.4)	0.2 (0.1)	521	720	762	781	199	241	260	-
2006	23.5 (11.1)	Downward	70.7 (21.5)	69.1 (20.6)	70.2 (21.2)	-1.6 (-0.9)	-0.5 (-0.3)	462	935	996	989	473	534	527	-
2007	29.4 (13.9)		70.9 (21.6)	69.6 (20.9)	71.1 (21.7)	-1.3 (-0.7)	0.2 (0.1)	472	908	958	947	436	486	475	-
2008	35.3 (16.7)		66.4 (19.1)	66.0 (18.9)	66.9 (19.4)	-0.4 (-0.2)	0.5 (0.3)	441	850	880	872	409	439	431	-
2009	41.2 (19.4)		73.0 (22.8)	70.9 (21.6)	72.5 (22.5)	-2.1 (-1.2)	-0.5 (-0.3)	435	942	935	929	507	500	494	-
2010	47.1 (22.2)		69.6 (20.9)	68.5 (20.3)	69.3 (20.7)	-1.1 (-0.6)	-0.4 (-0.2)	429	842	806	807	413	377	378	-
2201	23.5 (11.1)	Upward	81.9 (27.7)	87.6 (30.9)	85.5 (29.7)	5.7 (3.2)	3.6 (2.0)	387	788	800	939	401	413	552	0.727
2202			80.8 (27.1)	81.9 (27.7)	81.1 (27.3)	1.1 (0.6)	0.3 (0.2)	393	1081	1020	1083	688	628	690	0.997
2203			74.5 (23.6)	77.4 (25.2)	76.5 (24.7)	2.9 (1.6)	2.0 (1.1)	468	1006	951	1022	538	483	554	0.972
2204			75.0 (23.9)	75.9 (24.4)	75.6 (24.2)	0.9 (0.5)	0.6 (0.3)	441	955	928	959	514	487	518	0.993
2205	35.3 (16.7)		80.4 (26.9)	86.0 (30.0)	84.2 (29.0)	5.6 (3.1)	3.8 (2.1)	348	746	681	803	398	333	455	0.875
2206			78.8 (26.0)	77.7 (25.4)	77.9 (25.5)	-1.1 (-0.6)	-0.9 (-0.5)	433	925	899	904	492	466	471	1.044
2207			75.9 (24.4)	78.1 (25.6)	77.4 (25.2)	2.2 (1.2)	1.5 (0.8)	470	923	848	887	452	377	416	1.086
2208			73.4 (23.0)	74.1 (23.4)	73.9 (23.3)	0.7 (0.4)	0.5 (0.3)	436	875	839	854	439	403	418	1.052

to keep the pressure difference between the inside and outside of the experimental space equal to zero.

Of the earlier 10 experiments, five were carried out with upward ventilation, while the rest were carried out with downward ventilation. The average room air temperature at the end of occupancy varied between 64.8°F and 75.0°F (18.2°C and 23.9°C).

In the latter eight experiments, the ventilation rate was fixed to 23.5 cfm (11.1 L/s) for four and 35.3 cfm (16.7 L/s) for the rest; they were carried out with upward ventilation. To examine the influence of temperature difference, the average room air temperatures was changed from 73.4°F (23°C) to 86.0°F (30°C). The maximum temperature variations of supply air and average room air during the measurements were 0.9°F (0.5°C) and 2.7°F (1.5°C), respectively.

EXPERIMENTAL RESULTS

Room Content of CO$_2$

After CO$_2$ production at a rate of m starts at time $T = 0$, indoor and outlet CO$_2$ concentrations rise. The mass balance equation of CO$_2$ at any arbitrary time, T, is as follows. Here, the density change (by change in air temperature) is neglected.

$$\begin{aligned} M(T) &= Ci\,V + m\,T + Q\int Cs(T)\,dT - Q\int Ce(T)\,dT \\ &= Ci\,V + m\,T + Q\int \{Ce(T) - Cs(T)\}\,dT \end{aligned} \tag{1}$$

where

$M(T)$ = room content of CO$_2$ at time T, ft^3 (L),
Ci = initial ($T = 0$) indoor CO$_2$ concentration, ft^3/ft^3 (L/L),
V = volume of the room, ft^3 (L),
m = CO$_2$ production rate, cfm (L/min),
Q = ventilation rate, cfm (L/min),
$Cs(T)$ = CO$_2$ concentration of supply air at time T, ft^3/ft^3 (L/L),
$Ce(T)$ = CO$_2$ concentration of extract air at time T, ft^3/ft^3 (L/L),
T = time, min.

The terms on the right side of the above equation are the amount of CO$_2$ in the room from the beginning, produced, supplied with ventilation air, and extracted with ventilation air during dT.

CO$_2$ production by two persons, m, was 0.0165 cfm (28 L/h), which is calculated from the latter parts of the present experiments. The calculated room content of CO$_2$, $M(T)$, at time $T = 60$ minutes of the earlier 10 experiments is shown in Table 2 and Figure 2. The results of the experiments were used as the values of Ci, $Cs(T)$, and $Ce(T)$ to calculate $M(T)$. Note that $Ce(T)$ was different from the average CO$_2$ concentration in the room since the CO$_2$ was not in complete mixing. With upward ventilation, the lessening of the room content of CO$_2$ due to an increase in the ventilation rate was relatively small.

Ventilation Efficiency

Absolute ventilation efficiency in the transient condition, E^a, is defined as

$$\begin{aligned} E^a &= 1 - [\{M(T) - Ci\,V\}/\{m\,T + Q\int Cs(T)\,dT\}] \\ &= Q\int Ce(T)\,dT/\{m\,T + Q\int Cs(T)\,dT\}. \end{aligned} \tag{2}$$

The calculated absolute ventilation efficiency, E^a, after an occupancy of 60 minutes is shown in Table 2 and Figure 3. The rise of absolute ventilation efficiency due to increments of ventilation rate was relatively small in the case of upward ventilation.

Relative ventilation efficiency in a breathing zone in the transient condition, E^r, is defined as

$$E^r = \int \{Ce(T) - Cs(T)\}\,dT / \int \{Cb(T) - Cs(T)\}\,dT \tag{3}$$

TABLE 2
Calculated Room Content of CO_2 and Absolute Ventilation Efficiency at the End of Occupancy (T = 60 min)

Exp. No.	Ventilation Type	$\int Ce(T)dT$ ft³/ft³ (L/L) x min	$\int Cs(T)dT$ ft³/ft³ (L/L) x min	$\int Cb(T)dT$ ft³/ft³ (L/L) x min	Vent. Rate cfm (L/min)	CI ft³/ft³ (L/L) $\times 10^{-3}$	m cfm (L/min)	M(T) ft³ (L)	E^a	E^r
2001	Upward	0.0486	0.0275	0.0462	23.5 (667)	0.448	0.0165 (0.467)	1.08 (30.6)	0.70	1.13
2002		0.0462	0.0285	0.0444	29.4 (833)	0.442	0.0165 (0.467)	1.05 (29.8)	0.74	1.11
2003		0.0433	0.0271	0.0411	35.3 (1000)	0.423	0.0165 (0.467)	0.97 (27.5)	0.79	1.16
2004		0.0414	0.0275	0.0407	41.2 (1167)	0.432	0.0165 (0.467)	0.98 (27.9)	0.80	1.05
2005		0.0414	0.0294	0.0403	47.1 (1333)	0.437	0.0165 (0.467)	1.00 (28.2)	0.82	1.11
2006	Downward	0.0427	0.0277	0.0474	23.5 (667)	0.462	0.0165 (0.467)	1.24 (35.2)	0.61	0.76
2007		0.0417	0.0272	0.0442	29.4 (833)	0.422	0.0165 (0.467)	1.12 (31.6)	0.69	0.85
2008		0.0399	0.0257	0.0423	35.3 (1000)	0.423	0.0165 (0.467)	1.04 (29.5)	0.74	0.86
2009		0.0447	0.0268	0.0451	41.2 (1167)	0.453	0.0165 (0.467)	0.85 (24.0)	0.88	0.98
2010		0.0400	0.0254	0.0404	47.1 (1333)	0.406	0.0165 (0.467)	0.83 (23.6)	0.86	0.97

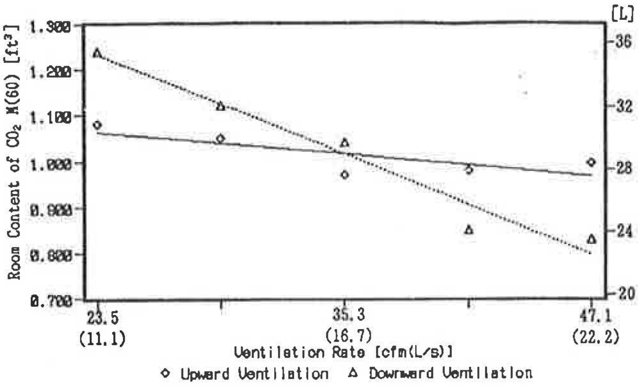

Figure 2 *Room contents of CO_2 at the end of occupancy (T = 60 min).*
Upward: $Y = -0.00390X + 1.154$ $R = -0.77$
Downward: $Y = -0.01847X + 1.668$ $R = -0.98$ *(Unit of X, Y: cfm, ft)*

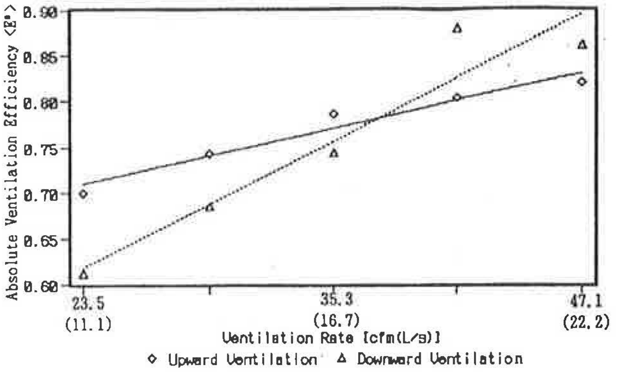

Figure 3 *Absolute ventilation efficiency at the end of occupancy (T = 60 min).*
Upward: $Y = 0.00518X + 0.588$ $R = 0.98$
Downward: $Y = 0.01177X + 0.341$ $R = 0.96$
(Unit of X: cfm)

where

$Cb(T)$ = CO_2 concentration in the breathing zone at time T, ft³/ft³ (L/L).

The calculated relative ventilation efficiency, E^r, after an occupancy of 60 minutes is shown in Table 2 and Figure 4. The relative ventilation efficiency was bigger than unity and decreased slightly with the increase of ventilation rate in the case of upward ventilation, while relative ventilation efficiency was smaller than unity and increased with the increase of ventilation rate in the case of downward ventilation.

Distributions of Room Air Temperature and CO_2 Concentration

Vertical distributions of room air temperature and CO_2 concentration for the latter eight experiments at the end of 120 minutes are shown in Figures 5 and 6. The temperature at every height in Figure 5 is the difference from the supply air temperature of the average of two measuring points at the same height. The temperature differences between the highest and lowest measuring points were 0.9°F (0.5°C) to 3.6°F (2.0°C). Since the fresh air was supplied at the lower part of the room, the CO_2 concentration was low at the lower part and was relatively high at the upper part. The CO_2 concentration was almost equal in the upper part. The height of the border, which is the lowest level of the high CO_2 concentration zone in the upper part of the room, was about

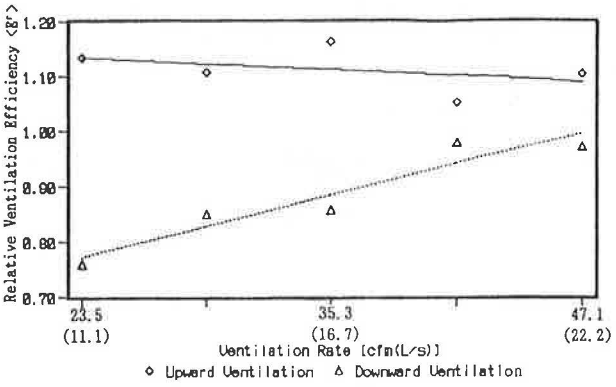

Figure 4 *Relative ventilation efficiency in breathing zone at the end of occupancy (T = 60 min).*
Upward: $Y = -0.00185X + 1.178$ $R = -0.43$
Downward: $Y = 0.00945X + 0.550$ $R = 0.95$
(Unit of X: cfm)

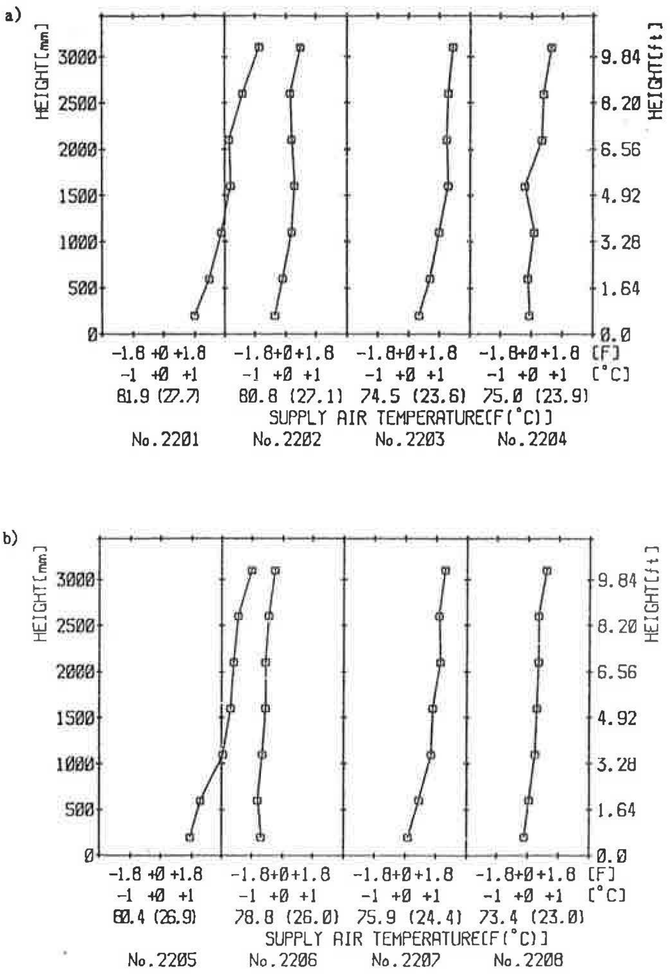

Figure 5 *Vertical distribution of room air temperature at the end of occupancy (T = 60 min).*
(a) Ventilation rate of 23.5 cfm (11.1 L/s)
(b) Ventilation rate of 35.3 cfm (16.7 L/s)

3.3 ft (1.0 m) above the floor with a ventilation rate of 23.5 cfm (11.1 L/s) and about 4.9 ft (1.5 m) above the floor with a ventilation rate of 35.3 cfm (16.7 L/s). In the lower part of the border, the gradient of CO_2 concentration to height was always positive but the shape was quite different in every experiment. The CO_2 concentration differences between the highest and the lowest measuring points were from 100 ppm to 650 ppm.

Influence of Temperature Difference

The temperatures of the supply air and extract air, the average room air temperature, and the differences of the latter two from the supply air temperature at the end of an occupied time of 120 minutes are shown in Table 1. The CO_2 concentrations of the supply air and extract air, the average CO_2 concentrations of the breathing zone and the room air, the differences of the latter three from the supply air CO_2 concentration, and the relative ventilation efficiency for the breathing zone at the steady condition, $\langle E^r \rangle$, which were calculated by Equation 4, are also shown in Table 1 (the average values are the arithmetical average of all measuring points).

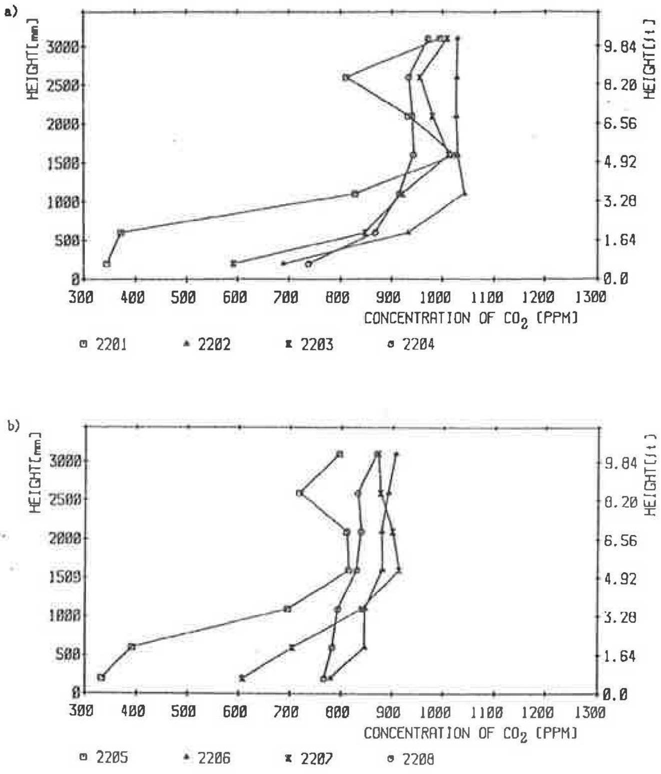

Figure 6 *Vertical distribution of CO_2 concentration at the end of occupancy (T = 60 min).*
(a) Ventilation rate of 23.5 cfm (11.1 L/s)
(b) Ventilation rate of 35.3 cfm (16.7 L/s)

$$\langle E^r \rangle = (Ce - Cs)/(Cb - Cs) \tag{4}$$

where

Ce = CO_2 concentration of extract air,
Cs = CO_2 concentration of supply air,
Cb = CO_2 concentration of breathing zone.

The relation of the differences between the average CO_2 concentration of room air and that of supply air and the difference between the average room air temperature and that of supply air is shown in Figure 7. When the difference of the average temperature of the room air and the supply air is positive, supplied fresh air stagnates in the lower part of the room by its density difference and makes the contaminated room air rise to the upper part of the room. Accordingly, the CO_2 concentration in the lower part of the room becomes low, and the average room CO_2 concentration is decreased. But the CO_2 concentration of the breathing zone is not low. The height of a front almost coincides with this zone. The low CO_2 concentration was below 2.0 ft (0.6 m) above the floor at

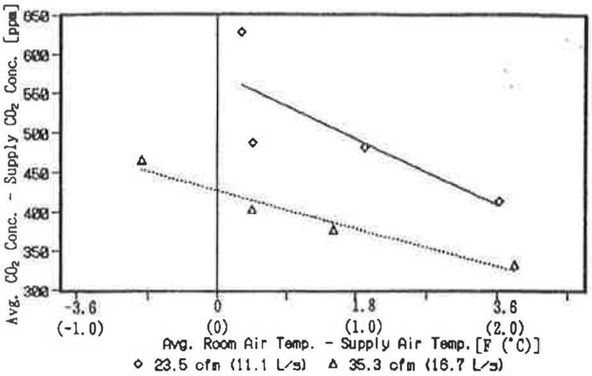

Figure 7 *Relations of CO_2 concentration rise and room air temperature rise in the experimental space.*
23.5 cfm: $Y = -83.19X + 575.59$ $R = -0.79$
35.3 cfm: $Y = -48.39X + 426.86$ $R = -0.98$
(Unit of X: °C)

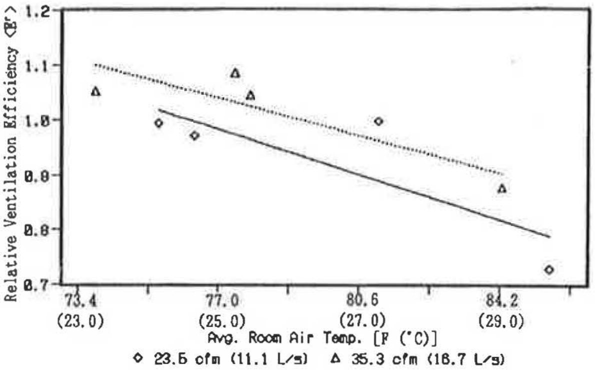

Figure 8 *Relation of relative ventilation efficiency and average room air temperature.*
23.5 cfm: $Y = -0.0417X + 2.0259$ $R = -0.82$
35.3 cfm: $Y = -0.0344X + 1.9005$ $R = -0.87$
(Unit of X: °C)

a ventilation rate of 23.5 cfm (11.1 L/s) and between 2.0 ft (0.6 m) and 3.6 ft (1.1 m) above the floor at a ventilation rate of 35.3 cfm (16.7 L/s).

The relation of relative ventilation efficiency and average room air temperature is shown in Figure 8. Generally, room air temperature is lower than body surface temperature. Low room air temperature makes a large difference between the body surface temperature and the average room air temperature, and the upward free convection due to the human subjects' metabolic heat increases. This makes the ventilation objects produced by human subjects rise, i.e., makes the relative ventilation efficiency for the breathing zone increase. The ventilation rate was nearly unity or more than unity when the average room air temperature was lower than 80.6°F (27°C). The ventilation efficiency became much lower than unity when the average room air temperature rose higher than 80.6°F (27°C). The CO_2 transportation effect by means of free convection around a human body seemed to have a border at around this temperature.

DISCUSSION

With downward ventilation, the absolute ventilation efficiency was lower than unity; i.e., a higher ventilation rate is needed for better indoor air quality. An increase in ventilation rate made the room CO_2 content lower. The absolute ventilation efficiency increased and approached unity. With upward ventilation, the decrease of room CO_2 content and the increase in the absolute ventilation efficiency due to the increase in ventilation rate are not so steep; i.e., the lower ventilation rate does not make the room air quality worse. In the present study, the CO_2 concentration of the breathing zone with a ventilation rate of 23.5 cfm (11.1 L/s) for two persons was around 1,000 ppm, which is indicated as good indoor air quality by ASHRAE. Therefore, it can be said that the ventilation rate for removing occupant-produced ventilation objects can be lowered to this amount.

If a room is completely divided into two zones—an upper polluted zone and a lower clean zone—and if the air in each zone is completely mixed, the fresh air supply needed to keep a breathing zone in the lower clean zone is about 85 cfm (40 L/s), which is the volumetric flow rate above a sitting body reported by Homma and Yakiyama (1988). But in reality, a room is not completely divided into two zones. From these results it can be said that there is some merit to applying an upward displacement ventilation system for good indoor air quality where human bodies are the main source of ventilation objects. The free convection around a body plays an important role in this.

To keep room CO_2 concentration low at a particular ventilation rate, the supply air temperature must not be higher than the average room air temperature. If the supply air temperature is higher than the average room air temperature, the supplied fresh air rises by its buoyancy force and the contaminated air descends. Then the room air is mixed. If the supply air temperature is too low, there are some risks of draft. Accordingly, it can be said that isothermal air supply at the low part of a room is ideal. Even if the supply air temperature is not lower than the average room air temperature, the upward free convection around a human body has sufficient force to carry CO_2 to the upper part of the room.

To keep the CO_2 concentration of a breathing zone low at a particular ventilation rate, the relative ventilation efficiency must be heightened. The upward displacement ventilation system utilizes the buoyancy force of the warm air around an occupant, which is lighter than ambient air. So it is better to keep the average room air temperature sufficiently lower than the body surface temperature; i.e., lower room air temperature results in higher relative ventilation efficiency of the breathing zone.

CONCLUSION

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 supply air and room air.

The earlier 10 experiments, in which the ventilation rates per person were changed, showed the following. With upward ventilation, the ventilation requirement per person, if the only contaminant source is the occupant, could be lessened to about 11.8 cfm (5.6 L/s) without exceeding a CO_2 concentration of 1,000 ppm in the breathing zone because the change of room content of CO_2 due to variation of the ventilation rate is influenced less by the upward ventilation system than by the traditional mixing system.

As an upward displacement ventilation system utilizes vertical CO_2 concentration differences by buoyancy force, the temperature conditions of the room work as an important factor. The latter eight experiments, where the supply air temperatures were changed, showed that room air temperature must be low and the supply air temperature must not be higher than the room air temperature to keep the CO_2 concentration in the breathing zone low.

Further studies are required to examine the effect of free convection in a room. The influence of various heat sources in a room should also be studied.

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