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DISTRIBUTION AND VENTILATION EFFICIENCY OF CO_2 PRODUCED BY OCCUPANTS IN UPWARD AND DOWNWARD VENTILATED ROOMS

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ABSTRACT

A ventilation method to attain improved indoor air quality with effective use of energy was examined in a small office-type experimental room. The experiments were carried out using human subjects, and the position of air supply and extract openings was changeable in the room. This paper reports the possibilities of ventilation efficiency improvement and the lessening of ventilation requirements when upward ventilation is compared to downward ventilation. The results indicated the following points: (1) due to upward free convection caused by the metabolic heat around a human body, upward ventilation always extracts CO_2 more efficiently than downward ventilation; (2) because the CO_2 concentration difference is increased between the upper and lower parts of a room by upward ventilation, ventilation efficiency becomes up to two times higher in upward ventilation than in well-mixed ventilation; (3) because upward ventilation extracts the air of higher CO_2 concentration than that of the breathing zone, it is possible to attain a ventilation efficiency higher than 100%.

INTRODUCTION

The basic purpose of ventilation is to create acceptable air quality indoors. The effective use of energy is an important consideration as well. Generally, the former is emphasized more than the latter. A method that realizes good air quality with effective use of energy is the subject of this study.

The free convection around a body has been shown to be an important element in room air mixing. Von Pettenkofer (1858) indicated that carbon dioxide concentration was higher in the upper part than in the lower part of an office. He inferred that expired air, into which the carbon dioxide was mixed, flowed upward with its buoyant force because its temperature and water vapor content were higher than those of room air. Houghten and Blackshaw (1933) reported in their ventilation requirement experiment that convective currents caused by occupants' heat dissipation effectively mixed the carbon dioxide and moisture of the occupants into room air.

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. In a study on body odor removal, 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.

The air velocity in the free convection plume above a sitting body was reported by Katz (1972) to be 30 fpm (0.15 m/s). Daws (1970) calculated the volume flow rate to be about 70 cfm (33 L/s) above a point heat source of 100 Btu/h (29 W), which corresponds to the convective heat dissipation of a human body. Homma and Yakiyama (1988) measured the volume flow rate to be 85 cfm (40 L/s) for a sitting body in a long-sleeved shirt and 87 cfm (41 L/s) for a sitting body in an undershirt. The plume flow above an occupant is several times larger than the fresh air requirement for body odor, which is 15 cfm (27 m^3/h [7.5 L/s]) for a person (ASHRAE 1989).

In rooms for sedentary occupation, such as classrooms, offices, and computer rooms, one of the main ventilation objectives is the 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 examined and understood carefully to be included in indoor environmental design. In this study, improvement of the extraction effect is investigated by upward ventilation compared to downward ventilation through experiments using human subjects.

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EXPERIMENTAL PROCEDURE

Space of Experiment

Inside a large, well-insulated laboratory, a small experimental room 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 were exchangeable at the upper and lower parts of the room. Supply air was forced by a fan from the buffer chamber, where the temperature was conditioned. By means of the inner pressure, the room air was extracted to the open air.

A plate was placed at the floor air in(out)let to restrict the inlet air velocity and to move the supply air horizontally. This arrangement prevents room air mixing by the induction effect of the supply air.

Experimental Subjects

Persons of normal Japanese physique were chosen from among university students and staff. In the experiments with two persons, efforts were made to keep a constant amount of metabolic heat and CO_2 generation by using the same subjects, who sat in the same position (chair is "2" in Figure 1). There were no rules for selecting the subjects and their seating position in the other experiments. During the experiments, subjects performed light work.

Measuring Methods

The floor plan was divided into two triangles by a diagonal line. The two sampling points of CO_2 and temperature were located at the centroids of the two triangles. At each of the locations, seven points of measurement were distributed vertically at heights of 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. To measure 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 of the all sampling points was passed to the concentration meter alternatively by controlling the solenoid valves. The concentrations of supply, extract, and outdoor air were also measured. Each concentration measurement took 20 seconds, and the total measuring time of the 18 sampling points was 120 seconds by the three concentration meters. Copper-constantan thermocouples were used for the temperature measurement. The measurement of concentration and temperature was repeated at an interval of three minutes.

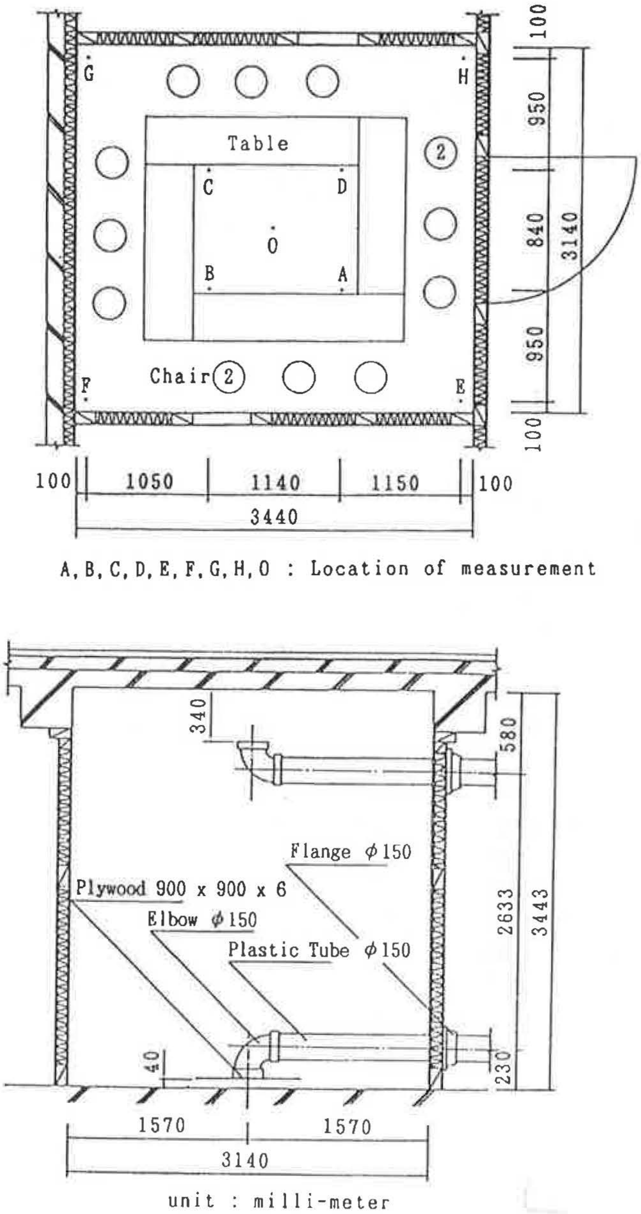

Figure 1 *Floor plan and vertical section of experimental space and locations of measuring points.*

The concentration meters were of infrared absorption type.

When the experimental room reached a steady condition, an experiment was started without subjects. Thirty minutes later, the subjects entered the room and stayed there for 60 minutes or a little longer. The measurement was continued for 30 minutes after the subjects left the room. Thirty experiments were carried out. The measurements are shown in Table 1.

To calculate the ventilation rate, the air velocity in the supply duct was measured with a hot wire anemometer.

In the latter parts of the experiments, the number of subjects was fixed to two, and ventilation rate was

TABLE 1
Experimental Conditions

Exp. No.	Venti-lation Type	Number of Sub-jects	Ventilation Rate per Person cfm (L/s)	Air Change Number 1/hr	Initial Room Temp. F (℃)	Initial Supply Air Temp. F (℃)	Initial Avg. CO2 Conc. ppm	Venti-lation Effi-ciency
1001		11	12.79 (6.04)	6.44	63.7 (17.6)	74.1 (23.4)	413	0.96
1002		4	14.15 (6.68)	2.59	63.3 (17.4)	70.2 (21.2)	452	1.00
1003		9	14.38 (6.79)	5.92	68.5 (20.3)	74.5 (23.6)	476	0.99
1004		10	17.02 (8.04)	7.78	76.1 (24.5)	76.6 (24.8)	426	0.94
1005		11	15.88 (7.50)	7.99	76.3 (24.6)	76.3 (24.6)	468	0.95
1006		10	17.47 (8.25)	7.99	78.1 (25.6)	78.4 (25.8)	459	1.00
1007		9	17.61 (8.32)	7.25	79.7 (26.5)	80.6 (27.0)	445	0.93
1008	Upward	2	23.29 (11.00)	2.13	68.4 (20.2)	75.4 (24.1)	472	1.01
1009		9	12.94 (6.11)	5.33	74.5 (23.6)	76.1 (24.5)	416	0.98
1010		6	22.11 (10.44)	6.07	64.9 (18.3)	66.2 (19.0)	435	1.18
2001		2	11.65 (5.50)	1.07	75.9 (24.4)	75.5 (24.3)	448	1.02
2002		2	14.56 (6.88)	1.33	68.9 (20.5)	69.6 (20.9)	442	1.10
2003		2	17.47 (8.25)	1.60	68.5 (20.3)	70.5 (21.4)	423	1.08
2004		2	20.38 (9.63)	1.86	64.0 (17.8)	69.3 (20.7)	432	0.91
2005		2	23.29 (11.00)	2.13	69.1 (20.6)	70.0 (21.1)	437	0.96
1011		10	15.21 (7.18)	6.96	66.2 (19.0)	66.6 (19.2)	450	0.93
1012		1	14.56 (6.88)	0.67	65.7 (18.7)	66.2 (19.0)	427	0.90
1013		9	13.30 (6.25)	5.48	66.6 (19.2)	67.1 (19.5)	437	0.91
1014		8	15.77 (7.45)	5.77	66.9 (19.4)	68.2 (20.1)	456	0.93
1015		10	14.56 (6.88)	6.66	68.7 (20.4)	69.4 (20.8)	430	0.91
1016		8	17.59 (8.31)	6.44	72.0 (22.2)	72.0 (22.2)	481	0.92
1017	Down-ward	10	14.56 (6.88)	6.66	74.0 (23.4)	72.5 (22.5)	466	0.90
1018		8	16.18 (7.64)	5.92	73.0 (22.8)	72.3 (22.4)	426	0.94
1019		2	16.50 (7.79)	1.51	73.9 (23.3)	72.3 (22.4)	448	0.91
1020		10	16.18 (7.64)	7.40	66.2 (19.0)	73.6 (23.1)	433	0.92
2006		2	11.65 (5.50)	1.07	68.5 (20.3)	69.4 (20.8)	462	0.86
2007		2	14.56 (6.88)	1.33	69.4 (20.8)	70.9 (21.6)	422	0.89
2008		2	17.47 (8.25)	1.60	65.8 (18.8)	66.0 (18.9)	423	0.92
2009		2	20.38 (9.63)	1.86	63.0 (17.2)	72.5 (22.5)	453	1.00
2010		2	23.29 (11.00)	2.13	67.3 (19.6)	69.1 (20.6)	406	1.01

changed to define the influence of variation of ventilation rate. These experiments were numbered starting at two thousand (see Table 1). In each type of upward and downward ventilation, five experiments were carried out with the two subjects.

EXPERIMENTAL RESULTS

Distribution and Timely Variation of CO_2 and Temperature in Experimental Room

Vertical distributions and timely variations of CO_2 and temperature are shown in Figure 2. They show that the upper part of the room had higher CO_2 concentration and temperature than the lower part. The CO_2 concentration and temperature altered with time nearly according to a logarithmic curve during the occupancy of the room. During occupancy, a difference of 100 to 300 ppm in CO_2 concentration existed between the highest and the lowest sampling points of the room in every experiment. Both the CO_2 and temperature distributions indicated the apparent effect of the free convection around occupants' bodies. The study emphasizes the ventilation phenomenon of CO_2.

It is easily thought that CO_2 concentration in the breathing zone might be the highest in the room. Actually, however, the CO_2 concentration is highest not in the breathing zone but above subjects' heads because of upward free convection.

Figure 3a shows variations of CO_2 concentration of supply air, extract air, and the air in the breathing zone (average value of heights of 3.6 ft [1.1 m] and 5.2 ft [1.6 m] above the floor) in the upward ventilation. The CO_2 concentration of the supply air was almost constant, and that of the extract air was a little higher than that of the breathing zone. Figure 3b shows the same variations in the downward ventilation. The CO_2 concentration of the extract air was a little lower than that of the breathing zone. This tendency was seen in all other experiments, and it can be said that the ventilation efficiency (efficiency of CO_2 extraction compared with arbitrary position) in the breathing zone can be raised to more than 100% by upward ventilation.

Partial Correlation Coefficient of Experimental Conditions

In this study, the ventilation efficiency was defined by Equation 1 according to the study by Sandberg (1981), which indicates the effectiveness of CO_2 distribution and the efficiency of CO_2 extraction compared with an arbitrary position.

$$E = (C_e - C_s)/(C_b - C_s) \qquad (1)$$

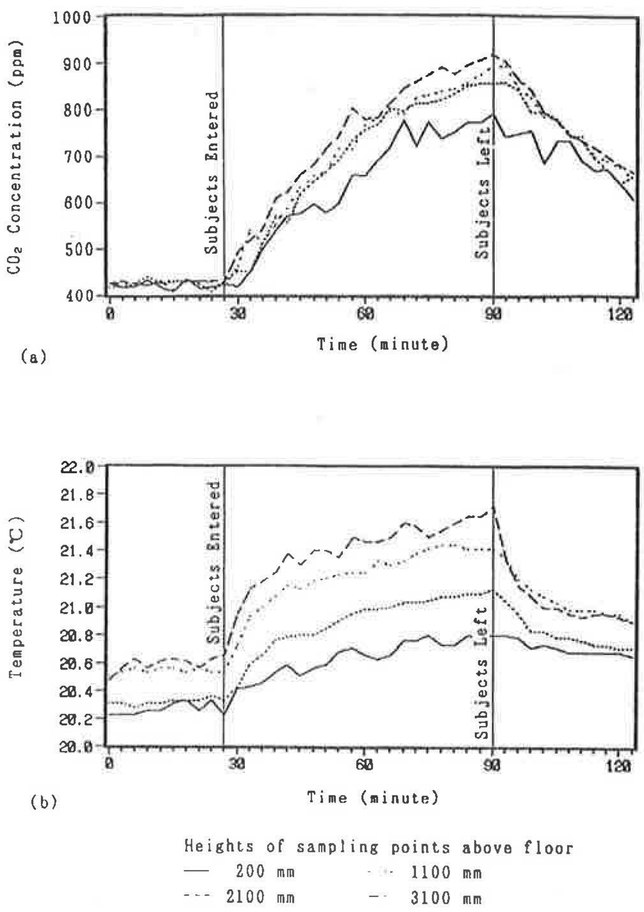

Figure 2 *Distribution and alternation of CO_2 and temperature of upward ventilation (experiment number: 2003).*

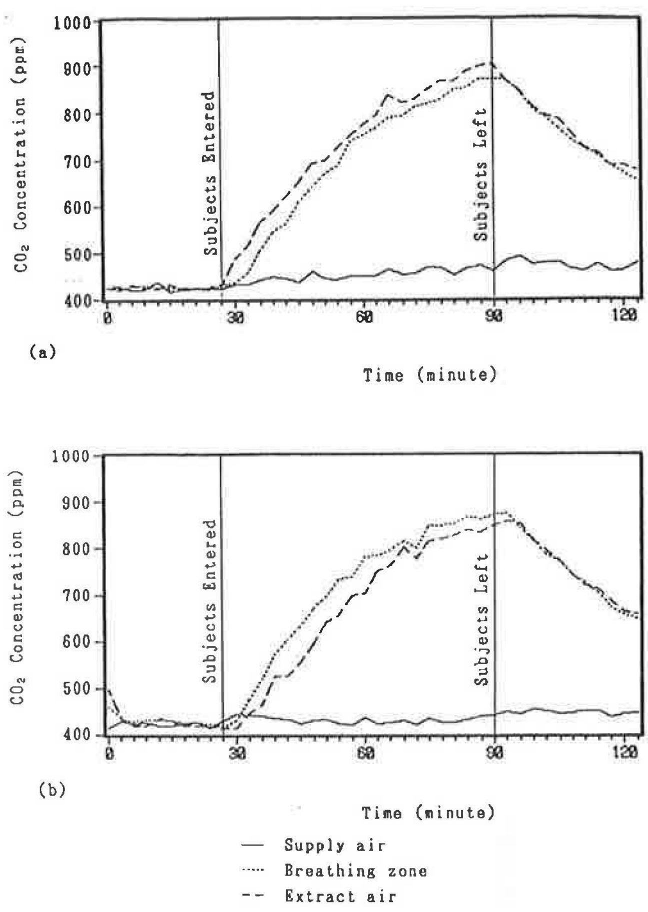

Figure 3 *Alternation of CO_2 concentration.*
(a) Upward ventilation (experiment number: 2003).
(b) Downward ventilation (experiment number: 2008).

where

E = ventilation efficiency,
C_e = CO_2 concentration of extract air (ppm),
C_s = CO_2 concentration of supply air (ppm),
C_b = CO_2 concentration of breathing zone (ppm).

The ventilation efficiency of each experiment is shown in Table 1. Note that the results of this calculation do not mean the absolute amount of CO_2 extracted but the relative concept of CO_2 concentration between extract air and the breathing zone. First, to define the influence of various experimental conditions on ventilation efficiency, a partial correlation analysis was executed (see Appendix). The results are shown in Table 2. Ventilation rate per person, air change number of the room, and initial temperature were selected as the independent variables. The partial correlation is considered to be significant statistically when the significant value P (the initial letter of probability) is less than 0.05; i.e., 95% of probability is needed for the partial correlation to be significant. With downward ventilation, the ventilation rate per person was only significant among the independent variables. A larger ventilation rate per person led to the higher ventilation efficiency. When the ventilation rate per person was large, the room air was stirred sufficiently by both the ventilation airstream and the free convection around occupants. When the ventilation rate per person was small, CO_2 was transported to the upper part of the room, where it stagnated. There was no significant correlation between the ventilation efficiency and the independent variables coefficient in the upward ventilation.

Second, to compare ventilation efficiencies in downward and upward ventilations, the same analysis was carried out with the results of all experiments. The ventilation types were added to the independent variables. In this analysis, to express the ventilation types in numerals, downward ventilation was denoted "0" and upward ventilation as "1." Table 3 shows the results of the analysis. Only partial correlation between ventilation efficiency and ventilation type showed significance. The ventilation efficiency of the upward ventilation was significantly higher than that of the downward ventilation.

TABLE 2
Partial Correlation Coefficients of Independent Variables for Ventilation Efficiency of Upward and Downward Ventilation of Whole Experiments

Independent Variable		Ventilation Rate per Person	Air Change Number	Initial Room Temperature
Upward	Partial Correlation Coefficient	0.022	-0.142	-0.188
	Significance	0.9 < P	0.6 < P < 0.7	0.5 < P < 0.6
Downward	Partial Correlation Coefficient	0.944	0.464	-0.495
	Significance	P < 0.01	0.05 < P < 0.1	0.05 < P < 0.1

TABLE 3
Partial Correlation Coefficients of Independent Variables for Ventilation Efficiency of Whole Experiments

Independent Variable	Ventilation Rate per Person	Air Change Number	Initial Room Temperature	Ventilation Type
Partial Correlation Coefficient	0.287	-0.041	-0.241	0.624
Significance	0.1 < P < 0.2	0.8 < P < 0.9	0.1 < P < 0.2	P << 0.01

Figure 4 shows the correlation of the ventilation types with the ventilation efficiency, which does not include the influence of any other factors. The significant value *P* was especially smaller than that of the partial correlations with other independent variables.

Time Variation in Distribution of CO_2 Concentration

In the experiments with two subjects, time variation in the distribution of CO_2 concentration was compared between the two types of ventilation. Figures 5 and 6 show the results. Each of the curves is a third-order regression curve by the least-squares method for the data of each height at each sampling time. Figure 5a shows the vertical distributions of CO_2 in upward ventilation 60 minutes after the occupancy of the room. The vertical distribution of CO_2 for the case of downward ventilation is shown in Figure 5b. For both ventilation types, it was confirmed that the average CO_2 concentration at every measuring height was decreased by the increase of ventilation rate. Figure 6 shows the vertical distribution of CO_2 of upward and downward ventilation with time. The curves are drawn at nine-minute intervals. The curves became closer as time proceeds and approached the steady condition at the end of 60 minutes.

Note that the shapes of the curves of vertical distribution differ according to ventilation type. The utilization of this difference may improve ventilation efficiency. Curves of downward ventilation (Figure 5b) show almost the same CO_2 concentration distribution with height, i.e., the room was well mixed. This is conventional ventilation, which needlessly ventilates all parts of a room and leads to loss of energy efficiency. Conversely, in the curves of upward ventilation (Figure 5a), CO_2 concentration increases with height. In the previous study about free convection around an occupant's body caused by its metabolic heat (Homma and Yakiyama 1988), it was indicated that the upward free convection reaches more than 1 ft above the occupant's head. In the upward

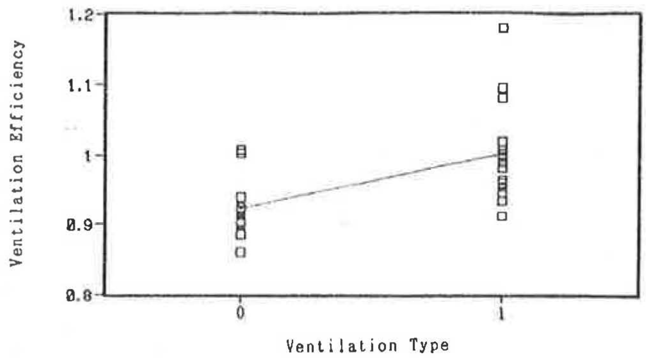

Figure 4 *Correlation of ventilation types with ventilation efficiencies.*
0 = downward ventilation
1 = upward ventilation
Line connects each average value of two types of ventilation system.

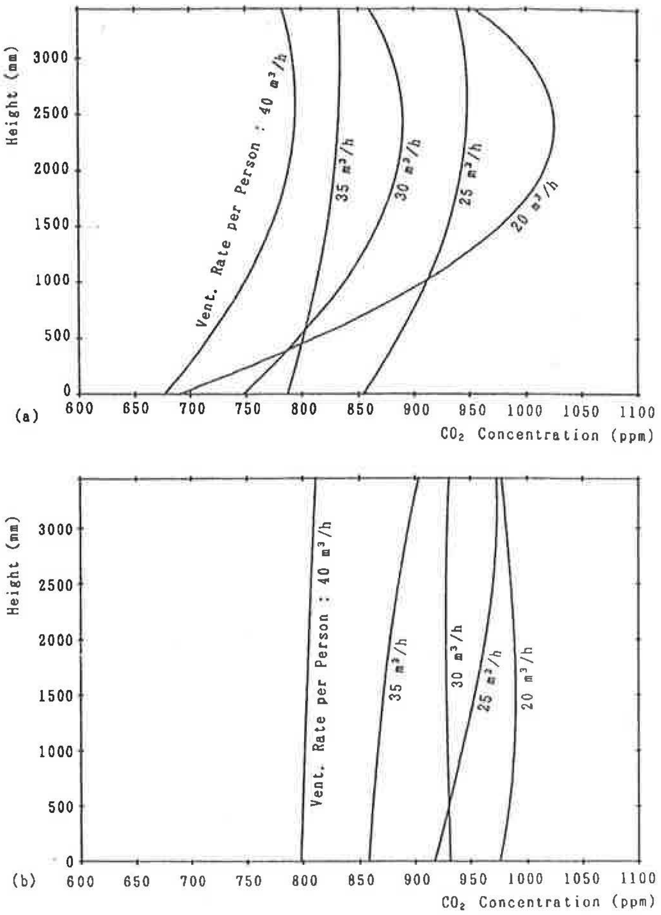

Figure 5 *Vertical distribution of CO_2 in two subject experiments at 60 minutes after occupancy.*
(a) upward ventilation
(b) downward ventilation.

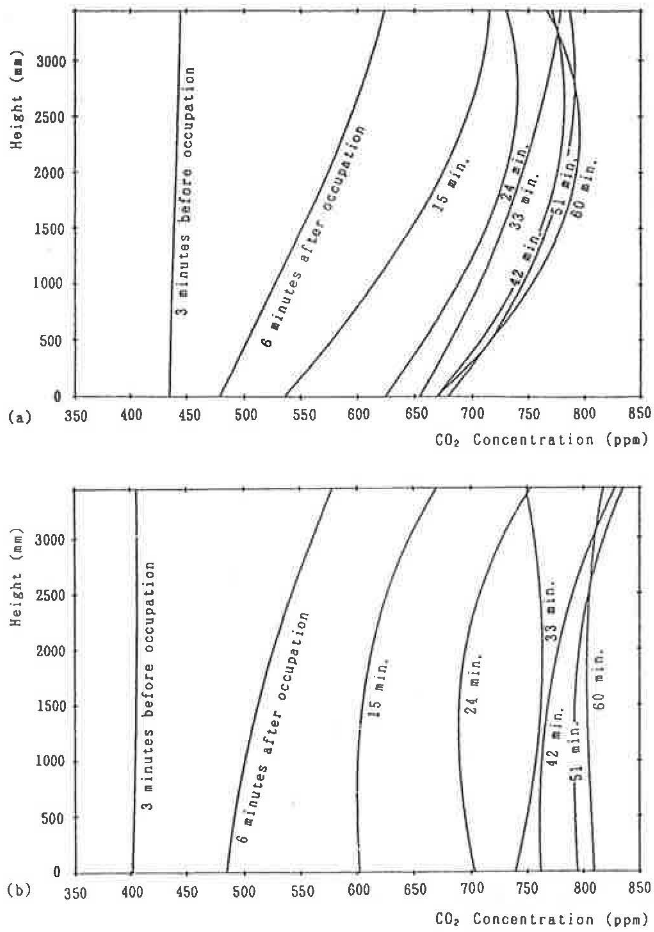

Figure 6 *Change in vertical distribution of CO_2 with time at nine-minute intervals.*
(a) upward ventilation (experiment number: 2005)
(b) downward ventilation (experiment number: 2010).

ventilation experiment, CO_2 concentration was highest at a height of about 3.3 ft (1.0 m) above the seated occupant's head, or about 8.2 ft (2.5 m) above the floor. It can be said that the upward free convection by the occupant's metabolic heat reaches this height with a mainstream of upward ventilation in the range of this ventilation rate. In an ordinary office, the ceiling height is close to this level. So by setting the extract port on the ceiling, the best extraction of ventilation subjects can be realized. To locate a supply port near the floor and an extract port near the ceiling produces a slight upward mainstream in a room. This stream is parallel to the body's free convection, so it does not disturb the upward flow of the occupant's effluents. An improvement in ventilation efficiency is realized by this type of ventilation.

Vertical Distribution of Temperature

The vertical distribution of air temperature is shown in Figure 7. Even though every experiment had different initial temperatures and supply temperatures, all had almost the same vertical distribution of temperature. Throughout the two subject experiments, the temperature of the upper part of the room was slightly higher than that of the lower part. Ventilation type had no visible influence on the vertical distribution of temperature.

The diffusion coefficient of CO_2 in air is 0.00891 ft^2/min (0.138 cm^2/s) and thermal diffusivity is 0.01236 ft^2/min (0.191 cm^2/s) at one atm, 32°F (0°C). Thermal diffusivity is one and a half times larger than the diffusion coefficient of CO_2 in air. Thermal distribution can easily become a state of equilibrium as compared with CO_2 distribution. Accordingly, thermal distribution is affected by ventilation type less than the distribution of CO_2.

Influence of Ventilation Rate on Ventilation Efficiency in Two Subject Experiments

The CO_2 concentrations in supply and extract air and in the breathing zone at the end of the occupied durations

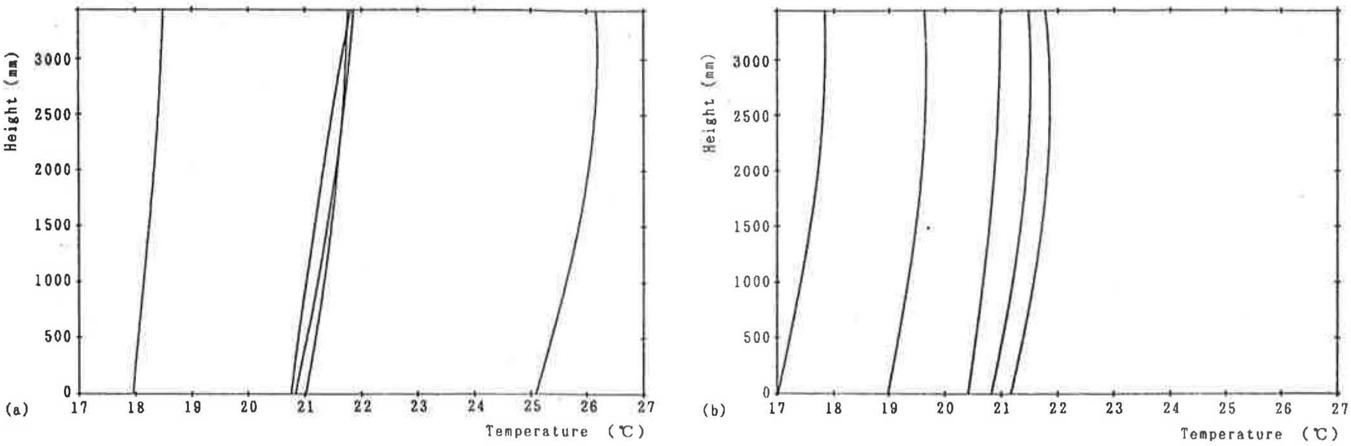

Figure 7 *Vertical distribution of temperature in two subject experiments at 60 minutes after occupancy. (a) upward ventilation; (b) downward ventilation.*

are indicated in Table 4. The ventilation efficiencies and the differences in the concentration of the breathing zone and of the extract air from that of the supply air are also shown in Table 4. It can be seen that the increased ventilation rate decreased the CO_2 concentration of the extract air and of the air in the breathing zone. In the cases of the same ventilation rate, upward ventilation always indicated a lower CO_2 concentration of air in the breathing zone.

However, when the ventilation efficiency is calculated with Equation 1, the above characteristic cannot be expressed. The ventilation efficiency showed higher values in the upward ventilation when the range of ventilation rate per person did not exceed 17.5 cfm (8.3 L/s). With the higher ventilation rates, the ventilation efficiency of the upward ventilation became smaller than that of the downward ventilation. However, the upward ventilation extracted CO_2 more effectively than the downward ventilation, and the CO_2 concentration in the breathing zone was lower in the upward ventilation than in the downward ventilation. It can be said that a large ventilation rate mixed the room air well, and the ventilation efficiency approached unity and was not influenced by the ventilation types.

In the downward ventilation, ventilation efficiency was less than unity when ventilation rates were small and approached unity as the ventilation rate increased. In this ventilation type, forced downward convection seemed to lessen the influence of upward free convection caused by the occupants' metabolic heat. In the upward ventilation, as ventilation rate increased, ventilation efficiency decreased from more than one to about one.

When the room air is mixed completely, ventilation efficiency becomes unity. When the ventilation rate is small, i.e., the room is not mixed completely, upward and downward ventilation act in different ways; upward ventilation makes a favorable distribution, while downward ventilation makes an unfavorable distribution for the ventilation system.

The ventilation efficiency cannot be expressed thoroughly by Equation 1, when a definite airflow exists and ventilation objects are transported by this airflow.

TABLE 4

CO_2 Distributions and Ventilation Efficiencies of Two Person Experiments

Exp. No.	Ventilation Rate per Person cfm (L/s)	Ventilation Type	Supply Air CO2 Conc. ppm	Breathing Zone CO2		Return Air CO2		Ventilation Efficiency
				Conc. ppm	Conc. diff.	Conc. ppm	Conc. diff.	
2001	11.7 (5.5)	Upward	463	908	445	919	456	1.02
2002	14.6 (6.9)		487	853	366	888	401	1.10
2003	17.5 (8.3)		460	812	352	841	381	1.08
2004	20.4 (9.6)		441	765	324	736	295	0.91
2005	23.3 (11.0)		506	753	247	744	238	0.96
2006	11.7 (5.5)	Downward	462	935	473	869	407	0.86
2007	14.6 (6.9)		458	876	418	828	370	0.89
2008	17.5 (8.3)		430	826	396	794	364	0.92
2009	20.4 (9.6)		442	805	363	806	364	1.00
2010	23.3 (11.0)		428	775	347	777	349	1.01

Comparison of Experimental Results with Assumption of Complete Mixing

The effective ventilation rate was calculated from the concentration decay after the subjects left the experimental room—when the free convection around the occupant's body disappeared but the vertical distribution was maintained. The following equation is a calculation of the ventilation rate from a decay of tracer gas concentration in a well-mixed room.

The effective ventilation rate is a theoretical quantity, not a physical flow rate. It can be both greater than or less than the nominal ventilation rate. When complete mixing occurs, it becomes equal to the nominal ventilation rate.

$$Q = \frac{V}{t} \ln \frac{C_1 - C_o}{C_t - C_o} \quad (2)$$

where

Q = ventilation rate, ft^3/h (m^3/h),
V = volume of room, ft^3 (m^3),
t = elapsed time, h,
C_1 = CO_2 concentration in room at initial measurement, ft^3/ft^3 (m^3/m^3),
C_t = CO_2 concentration in room at final measurement, ft^3/ft^3 (m^3/m^3),
C_o = CO_2 concentration in supply air, ft^3/ft^3 (m^3/m^3).

The arithmetical 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 the subjects left. The result is shown in Table 5. The ratio in the table is the proportion of the calculation to the experimental ventilation rate. When a room is ventilated using an upward stream, CO_2 can be extracted more effectively than in the well-mixed condition, as these ratios indicate. It is possible to heighten ventilation efficiency and to lessen the ventilation rate requirement by using the directional stream.

CONCLUSIONS

Distribution of CO_2 in the experimental room was indicated to be influenced significantly by the free convection caused by the occupants. The upward stream of the free convection was found to strongly influence ventilation efficiency. When the mean airstream of ventilation coincides with the free convection, the ventilation efficiency rises. When the direction of the mean airstream of ventilation is against the free convection, the ventilation efficiency decreases. The following points should be considered in ventilation design:

1. When there is a main direction in the room airstream, the distribution of ventilation subjects is influenced by its direction, even if its speed is negligible.
2. Upward ventilation always extracts CO_2 more efficiently than downward ventilation, due to the upward free convection caused by the metabolic heat around a human body.
3. Upward ventilation extracts one and a half times more CO_2 than a ventilation system in a well-mixed room.
4. It is possible to make ventilation efficiency higher than 100% by means of upward ventilation.

Further studies are required to examine decreased ventilation rate. The influence of different air temperatures and various heat sources in a room should also be studied further.

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TABLE 5
Comparison of Ventilation Rates per Person of Experimental Condition and Estimation from CO_2 Decay

Exp. No.	Ventilation Type	Experimental Condition cfm (L/s)	Result of Calculation cfm (L/s)	Ratio
2001	Upward	11.7 (5.5)	22.5 (10.6)	1.92
2002		14.6 (6.9)	19.9 (9.4)	1.36
2003		17.5 (8.3)	22.6 (10.7)	1.29
2004		20.4 (9.6)	33.5 (15.8)	1.64
2005		23.3 (11.0)	41.8 (19.7)	1.79
2006	Downward	11.7 (5.5)	13.6 (6.4)	1.16
2007		14.6 (6.9)	19.6 (9.3)	1.34
2008		17.5 (8.3)	20.5 (9.7)	1.17
2009		20.4 (9.6)	19.2 (9.1)	0.94
2010		23.3 (11.0)	29.5 (13.9)	1.27

REFERENCES

ASHRAE. 1989. *ASHRAE Standard 62-1989, Ventilation for acceptable indoor air quality*. Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Daws, L.F. 1970. Movement of air stream indoors. *J.I.H.V.E.* 37 (Feb.): 241-253.

Fisher, R.A. *Statistical methods for research workers*. London: Oliver & Boyd Ltd.

Homma, H., and M. Yakiyama. 1988. Examination of free convection around occupant's body caused by its metabolic heat. *ASHRAE Transactions* 94(1): 104-124.

Houghten, F.C., and J.L. Blackshaw. 1933. Indices of air change and air distribution. *ASHVE Transactions* 39: 261-276.

Japan Industrial Standard No. A1406-1974, Measuring method of indoor ventilation rate, carbon dioxide method.

Katz, P. 1972. Luftgeschwindigkeiten im klimatiserten Raum. *Luftung, Heizung und Hausteknik* 23 (Sept.): 295-298.

Lewis, E., A.R. Foster, B.J. Mullan, R.N. Cox, and R.P. Clark. 1969. Aerodynamics of the human microenvironment. *The Lancet*, 28 June: 1273-1277.

Nielsen, M., and L. Pedersen. 1952. Studies on the heat loss by radiation and convection from the clothed human body. *Acta Phys. Scandinav.* 27: 272-294.

Sandberg, M. 1981. What is ventilation efficiency? *Building and Environment* 16(2): 123-135.

Sandberg, M. 1983. Ventilation efficiency as a guide to design. *ASHRAE Transactions* 89(2B): 455-479.

von Pettenkofer, M. 1858. Uber den Luftwechsel in Wohngebauden. *Literarisch-Artistische Anstalt*: 23-25. Munchen.

Yaglou, C.P., E.C. Riley, and D.I. Coggins. 1936. Ventilation requirement. *Heating, Piping and Air-Conditioning* (Jan.).

APPENDIX

When there are many variables with experimental conditions that affect ventilation efficiency, it is important to know how much each variable affects it. Partial correlation coefficients are very effective for this purpose. These express the correlation between one independent variable and the dependent variable independently of the influences of the other independent variables.

The partial correlation coefficients with two independent variables could be calculated by the following equation:

$$r_{y1.2} = \frac{r_{1y} - r_{2y} r_{12}}{\sqrt{(1 - r_{2y}^2)(1 - r_{12}^2)}} \tag{A1}$$

where

$r_{y1.2}$ = partial correlation coefficient between independent variable x_1 and dependent variable y independently of the influence of independent variable x_2,

r_{ab} = total correlation coefficient between variables a and b.

Matrix R of the correlation coefficient of x_1, x_2, and y, its inverse matrix R^{-1}, and its determinant $|R|$ could be set as follows:

$$R = \begin{bmatrix} 1 & r_{12} & r_{1y} \\ r_{12} & 1 & r_{2y} \\ r_{1y} & r_{2y} & 1 \end{bmatrix} \quad R^{-1} = \begin{bmatrix} r^{11} & r^{12} & r^{1y} \\ r^{12} & r^{22} & r^{2y} \\ r^{1y} & r^{2y} & r^{yy} \end{bmatrix} \tag{A2}$$

$$|R| = 1 - r_{12}^2 - r_{1y}^2 - r_{2y}^2 + 2\, r_{12}\, r_{1y}\, r_{2y}\,.$$

These are changed as follows:

$$\begin{aligned} r^{11} &= (1 - r_{2y}^2)/|R|, \\ r^{yy} &= (1 - r_{12}^2)/|R|, \\ r^{1y} &= (r_{12} r_{2y} - r_{1y})/|R|. \end{aligned} \tag{A3}$$

From Equations A1 and A3, the following equation is obtained:

$$r_{y1.2} = \frac{-r^{1y}}{\sqrt{r^{11} r^{yy}}}. \tag{A4}$$

When the number of independent variables is p, the equation for calculating the partial correlation coefficient is expressed as follows:

$$r_{yn.1,2,\ldots,(n-1),(n+1),\ldots,p} = \frac{-r^{ny}}{\sqrt{r^{nn} r^{yy}}}. \tag{A5}$$

The probability P, which expresses the significance of the partial correlation, checks the significance of the partial correlation. The value of P is found in a table in a book of statistics using the values of the partial correlation coefficient and the number of data.

Even if the values of the partial correlation coefficient are the same in two or more analyses, when the number of data is different, the probability is not always the same.