INFLUENCE OF FREE CONVECTION OF OCCUPANTS' METABOLIC HEAT ON VERTICAL DISTRIBUTION OF CARBON DIOXIDE IN CLASSROOM

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1. INTRODUCTION

Thermal insulation and air tightness of building envelopes are developing rapidly. Room air movement is reduced considerably by the development. The natural room air movement is caused by the temperature difference between the room air and the wall surfaces, and also by the air flow into and from the room in an unoccupied condition. Besides, upward free convection is caused above an occupant's body by its metabolic heat dissipation. When the natural room air movement is reduced, the influence of the free convection around an occupant's body increases its relative effect on the movement of contaminants in a room.

The search for higher ventilation efficiency has been conducted by tracing the movement or distribution of contaminants in a room. One way of this research is the numerical simulation of room air movement using Navier-Stokes equation, into which the contaminant transportation by the air movement is combined [1]. This method requires complicated treatment and long calculation time of a high speed computer to treat the delicate balance of forces in the air movement. The other way of the ventilation efficiency study is the simulation of contaminant concentration by the two region ventilation model. The model has been established well by Pham and Skaret et al. [2,3]. This model is simple but practical to treat the vertical stratification of contaminants in a room.

The vertical gradients in carbon dioxide concentration in rooms were already recorded in Pettenkofer's work of 1858 [4]. Houghten and Blackshaw suggested in their minimum ventilation requirement study that the free convection around occupants had the generative force of the uniform mixing of the room air [5]. In Yaglou and his colleague's study on body odour removal, they defined the effective air supply as the air flow, which passed over the occupied zone, and therefore removed the products of respiration and transpiration [6]. It is evident from these studies that these researchers considered the effect of free convection caused by the occupants on the ventilation efficiency.

In the present study, the influence of the free convection around occupants' bodies on transportation of the ventilation objectives, which are produced by the room occupants, is examined experimentally and numerically according to the following ways. 1) the vertical distribution of occupant produced carbon dioxide was measured in a classroom. 2) the two region numerical model of ventilation was modified to include the effect of the free convection around occupants on the vertical distribution of carbon dioxide. 3) the influence of location of air supply and extract openings on ventilation effectiveness was examined using the modified two region numerical model.

2. MEASUREMENT OF DISTRIBUTIONS OF CARBON DIOXIDE AND TEMPERATURE IN CLASSROOM

2.1 MEASUREMENT OBJECTIVES

Various materials are respirated or transpirated from a human body as ventilation objectives. Carbon dioxide was chosen from the materials as the tracing medium of the ventilation objectives' movement. Carbon dioxide is approximately 50 % heavier than the air. In the present study, it was assumed that ventilation objectives flow upward transported by the free convection around a body. A heavier material than the air was convenient to examine this assumption. The diffusion of body heat in the classroom was also examined by the measurement of air temperature distribution.

2.2 TEST ROOM

For the test, a classroom was chosen from one of the buildings of Toyohashi University of Technology. The classroom was convenient for the experiment, because the numbers of occupants varied in a wide range, and because the lecture time was limited to 75 minutes. The air in the classroom was changed with fresh air during the breaks, and the measurements were repeated with the new initial conditions.

The plan of the tested classroom is shown in figure 1. It had the horizontal floor and ceiling of a height 3.00 m. Its floor area and volume were 78.6 m^2 and 235.7 cub.m, respectively. The east wall consisted of a single glass window from a height of 0.89 m above the floor to the ceiling. The window frames were made of extruded alminium. The two thirds of the window area was openable sliding windows. Plastic weather strips were attached to the window frames. The external walls and partitions were made of reinforce concrete of a thickness 15 cm. Thermal insulation was not applied on them. Two sets of doors of a width of 1.2 m and a height of 2.05 m were installed on the northern and southern ends of the west partition. A transom of a height of 0.7 m and a width of 1.2 m was prepared above each of the door sets.

This classroom had not a mechanical ventilation system. It was aired through the large windows on the east wall, and through the transoms on the west partition by wind force in the summer. It changed air with the corridor through the slits beneath the doors, and through the tilted transoms by thermal buoyant force in the winter. One end of the corridor connected to outdoor without a door. During the experiments, some of the doors, which connected the corridor to outdoor, were kept open to reduce carbon dioxide concentration in the corridor.

2.3 EXPERIMENTAL CONDITIONS

The experiments were carried out in Novembers of 1985 and 1986. These periods were chosen because outdoor temperature was lower than the indoor temperature in the daytimes, but the heating was not yet started. The wall temperature was not so low that the down draught on the wall surfaces was weak. The lectures were carried out without opening the windows.

2.4 MEASURING METHOD

The measurement in November 1985 was carried out with the two transoms open. The total opening area of the transoms was approximately 0.9 m^2, and that of the slits beneath the doors was 0.07 m^2. Carbon dioxide concentration was measured at the two places, which are shown in figure 1. The sampling points were distributed at heights of 0.50, 1.35, 2.00 and 2.80 m above the floor of each of the two measuring places. Only one concentration meter was used. Every sampling point were connected to the concentration meter with plastic tubes of a diameter 6 mm. A solenoid valve was attached to the end of each of the sampling tubes. The air of the all sampling points were passed to the concentration meter alternatively by controlling the solenoid valves. A concentration measurement took 20 sec. for a point, and the total measuring time of the 8 sampling points was 160 sec. The temperature sensors were also located at the same points as the concentration measurements. Besides, wall, ceiling and floor surface temperatures were measured at 21 points, which are shown in figure 1, to calculate the down draught on the surfaces. Copper-constantan thermocouples were used for the temperature measurement. The measurement of concentration and temperature was repeated at an interval of 5 minutes. The used concentration meters were of infrared absorption type. The performance of the carbon dioxide concentration meter, which was used in the experiment in 1985, had measuring ranges of 2000 and 5000 ppm and its maximum error was 5 % of the used range. The concentration meters, which were added for the 1986 experiment, had a measuring range of 10 000 ppm. Its maximum error was 10 % of the indicated value.

The experiment of November 1986 was carried out with the transoms closed. The measuring places were increased to 5 places, as shown in figure 1. Three sampling points were distributed at heights 0.5, 1.5 and 2.5 m above the floor at each of the places. Concentration was measured also beside one of the transoms and in the corridor and outdoor. Three carbon dioxide concentration meters were used in this experiment. The concentration meters were calibrated carefully with the reference concentration gases to avoid deviation among the meters. Further, the sample air at the same point was sucked to the three concentration meters at the same time to examine the difference in the performance of the meters in some of the measurements. The temperature measurement was done in the same way as the experiment of 1985.

One lecture was treated as one measurement. Nominal time of a lecture was 75 min., and a break of 10 min. was assigned between lectures. But this time was not always kept punctually. During the breaks, all occupants left the classroom, and the room air was changed by opening the windows by the experiment attendant. The attendant waited in the corridor during the measurements and recorded the changes in number of the occupants, opening and closing of the doors and transoms, and weather conditions.

16 measurements were carried out from 5th to 22nd of November in the experiment of 1985. 13 measurements were carried out from 18th to 26th of November in the experiment of 1986. The conditions of the measurements are shown in tables 1 and 2. The wind speeds in the tables were measured at a height of 18 m in the university campus with an ultrasonic wind speed meter.

The ventilation rate of the classroom was measured under unoccupied condition just before the experiment period of 1985 by the tracer gas decay method. During this measurement, the wind direction was north-west, which is the mean wind direction in this season in this district, and the average wind speed was 8.3 m/s. The measured air change rate was 89 cub.m/h.

3. RESULTS OF MEASUREMENTS

The concentration changes at one of the upper measuring points and one of the lower measuring points in one of the measurement on Nov. 5, 1985 are shown in figure 2 a. The temperature changes and the change in number of the occupants are shown in figure 2 b. The average number of the occupants were 43. The concentration reached to 3400 ppm at the upper measuring points in the end of the lecture. The concentration at the upper sampling points was definitely higher than those at the lower sampling points throughout the measurement. The temperatures at the upper and the lower measuring points separated each other. But the concentration at the lower measuring points arose considerably with the lapse of time. This means that the air was mixed strongly in the classroom, while the air flow pattern was upward displacement flow from the cracks beneath the doors to the open transoms.

The concentration changes at one of the upper measuring points and at one of the lower measuring points in one of the measurement on Nov. 18, 1986 are shown is figure 3. The average number of the occupants was 15. The concentration reached to 2300 ppm at the upper measuring points in the end of the lecture. The concentrations at the upper and lower measuring points separated definitely.

The main characteristics of the results of experiments of 1985 and 1986 are shown in tables 1 and 2, respectively. The indicated air change rate was calculated from the average concentration change of all of the measuring points and carbon dioxide production of the occupants by an iterative method to include the change in the number of occupants during the measurement. The carbon dioxide production was assumed to be 22 L/h·person, which is the standard value for a normal Japanese person. The natural air change force seemed to be too weak to keep the room air clean. A clear proportional relation was recognized between the ventilation rate and the number of the occupants. This indicates that the air change was influenced by the thermal buoyancy, which was casued by the occupants' heat dissipation.

The relations between the average concentrations at the upper two measuring points and that at the lower two measuring points of all of the 16 measurements of 1985 are shown in figure 4. Almost all the marks deviated to the upper part of the equivalent line of 45°. Their deviations were stronger in the higher concentration region than in the lower concentration region. The concentrations of the upper measuring points were averagely 300 ppm higher than those of the lower measuring points, when the concentration at the lower measuring points was 3000 ppm. The higher concentration in the upper part of the room indicates that the carbon dioxide flowed upward, when it was released into the room.

Figure 5 shows the relations between the average concentrations at the upper five measuring points and those at the lower five measuring points of all the measurements in 1986. The air flow pattern of the classroom might be horizontal cross flow, in which the air entered into the classroom through the cracks around the doors and transoms of the west partition, and left the room through the window cracks on the east wall by wind pressure. The plots of the relations can be classified into the following four groups according to the measured conditions.

When the number of the occupants was smaller than 29, and the elapsed time was shorter than 25 min., the concentration was less than 1500 ppm in both of the upper and the lower regions. The concentration difference between the two regions was small. The concentration in the upper region arose, when the elapsed time was longer than 30 min., but the concentration in the lower region did not arose as much as that in the upper region. This suggests that the mixing by the free convection around the occupants was weak, because the number of the occupants was small.

When the number of occupants was larger than 30, the concentration in the upper region arose as soon as the lecture started, but that in the lower region did not yet arose. This made the difference in concentration between the two regions large. When the elapsed time was more than 30 min., the concentration of the two regions approached each other. This suggests that there was a sufficient air interchange between the two regions.

As seen from the above results, the plume flow above the occupants seemed to have strong effect to transport the carbon dioxide upward, and also to mix the room air vertically.

4. INCORPORATION OF PLUME FLOW IN TWO REGION VENTILATION MODEL

The two region ventilation model has been developed and well established to examine ventilation efficiency of a room, see Pham and Skaret et al. [2,3]. A simulation method was developed from the two region model to examine some factors, which concern to the vertical difference of the carbon dioxide concentration. The classroom was supposed to be divided into two regions horizontally. The lower one of which was the occupied region, and the upper one was the overhead region. Occupants of the classroom respirate in the occupied region. The following basic conditions were considered.

a) the contaminant, which was produced or flowed into each region, was mixed instantaneously and homogeniously in each region.

b) the contaminant was produced by the occupants, who lived in the occupied region. But it flowed directly into the overhead region without diluting in the occupied region.

The radius of the temperature plume above a body increases with hight [7,8]. So the room air around the plume is induced into the plume, and the carbon dioxide in the plume is supposed not to dilute into the occupied zone. Body odor, which is produced on a body surface, is mixed in the thermal plume above the body, and transported upward by the plume. The free convection visualization experiment with an infrared camera indicated that the expired air did not flow separately, but it was included in the plume, and flowed upward with the plume.

c) the increase of air volume by the temperature rise is negligible.
d) the contaminant is not adsorbed on various surfaces in the room.
e) the contaminant does not react chemically with the room air.

The definitions, which were used by Skaret, were employed for the present two region ventilation model with modification. The model is shown in figure 6. The plume flow and the down draught on wall surfaces were adopted as the air interchange between the two regions into the basic two region model. The volume V of the classroom was divided into the overhead and the occupied regions, the fractions of which were Z and (1-Z), respectively. The total ventilation rate of the classroom was Q, of which the fraction X flowed into the overhead region, and the rest of it flowed into the occupied region. The fraction Y of the ventilation rate left the overhead region, and the rest of it left the occupied region. The upward air stream $A \cdot Q$ was the plume flow above the occupants, which was evaluated by multiplying the volume flow of the plume above an occupant by the number of the occupants. The total quantity of down draught along the wall surfaces $B \cdot Q$ flowed from the overhead region to the occupied region. The air flow $C \cdot Q$ was assigned to satisfy the continuity of the air flows in each of the regions. M was the production rate of carbon dioxide by the occupants.

Using the above definitions, and supposing the changes in carbon dioxide concentration in the two regions to be dC_1 and dC_2 in a infinite time difference dt, the conservation of the carbon dioxide in the two regions are,

$$K \cdot V \cdot dC_1 = X \cdot Q \cdot C_0 \cdot dt + A \cdot Q \cdot C_2 \cdot dt + U \cdot C \cdot Q \cdot C_2 \cdot dt + M\, dt \qquad (1)$$

$$- (Y + B + \bar{U} \cdot C) \cdot Q \cdot C_1 \cdot dt$$

$$(1-K) \cdot V \cdot dC_2 = (1-X) \cdot Q \cdot C_0 \cdot dt + B \cdot Q \cdot C_1 \cdot dt + \bar{U} \cdot C \cdot Q \cdot C_1 \cdot dt \qquad (2)$$

$$- (1 - Y + A + U \cdot C) \cdot Q \cdot C_2 \cdot dt$$

Where U and $\bar{U}$ are unit functions, and mean

$U = 0$ and $\bar{U} = 1$, when $C \cdot Q$ is positive

$U = 1$ and $\bar{U} = 0$, when $C \cdot Q$ is negative

C_0 is the carbon dioxide concentration in the outdoor air.

These equations make a series of differential equations, when the both sides of the equations are divided by dt. The solutions of these equations express the changes in carbon dioxide concentration in the two regions as shown below,

$$C_1 = [(a - m_2) \cdot c \cdot \exp(a \cdot t) + (b - m_2) \cdot d \cdot \exp(b \cdot t)]/n_2 + J_1 \qquad (3)$$

$$C_2 = c \cdot \exp(a \cdot t) + d \cdot \exp(b \cdot t) + J_2 \qquad (4)$$

Where $w_1 = (X \cdot Q \cdot C_0 + M)/K \cdot V$ $\quad n_1 = (A + U \cdot C) \cdot Q/K \cdot V$ $\quad m_1 = -(Y + B + \bar{U} \cdot C) \cdot Q/K \cdot V$

$w_2 = (1-X) \cdot Q \cdot C_0/(1-K) \cdot V$ $\quad n_2 = (B + \bar{U} \cdot C) \cdot Q/(1-K) \cdot V$ $\quad m_2 = -(1 - Y + A + U \cdot C) \cdot Q/(1-K) \cdot V$

$$a = ((m_1 + m_2) + \mathrm{sqrt}[(m_1 + m_2)^2 - 4(m_1 \cdot m_2 - n_1 \cdot n_2)]) / 2$$

$$b = ((m_1 + m_2) - \mathrm{sqrt}[(m_1 + m_2)^2 - 4(m_1 \cdot m_2 - n_1 \cdot n_2)]) / 2$$

$$c = - ((b - m_2)(C_{20} - J_2) - n_2(C_{10} - J_1)) / (a-b)$$

$$d = ((a - m_2)(C_{20} - J_2) - n_2(C_{10} - J_1)) / (a-b)$$

$$J_1 = (n_1 \cdot w_2 - m_2 \cdot w_1)/(m_1 \cdot m_2 - n_1 \cdot n_2) \qquad J_2 = (n_2 \cdot w_1 - m_1 \cdot w_2)/(m_1 \cdot m_2 - n_1 \cdot n_2)$$

Where C_{10} and C_{20} are the initail concentrations in the overhead and occupied regions, respectively.

Mierzwinski indicated the volume flow above the head of a seated or standing body in a room of a temperature of 19 to 23 °C to be between 108 and 216 cub.m/h [7]. One of the authors made a measurement of the plume flow above the 15 subjects in a room temperature of between 24.5 and 26.5°C. The average volume flow above the seated subjects in undershirts was 147 cub.m/h, and that above the seated subjects in long sleeve wooven shirts was 144 cub.m/h at a height of 2 m above the floor. There was not data for volume flow above a group of bodies. In the present simulation, 120 cub.m/h·person was chosen.

The down draught Qw along a wall of a length of L at a distance of X beneath the ceiling is calculated by the following equation [9].

$$Qw = (X^3 \cdot g \cdot dT \cdot Nu^2 / T)^{0.25} \cdot L \qquad (5)$$

Where g is the gravitational acceleration, T is the absolute temperature of air, dT is the temperature difference between the air and the wall surface, and Nu is the kinematic viscosity of the air.

The changes in concentration in the two regions were calculated for the same condition as the measurement of Nov. 5, 1985 using equations (3) and (4). The division was assumed at a height of 2 m above the floor. The chosen ventilation rate 310 cub.m/h for the simulation was attained from the measured average concentration, and the carbon dioxide producion was 22 L/h·person. The number of the occupants varied with time in the lectures, so the simulation time was divided into several segments, in each of which the number of occupants was steady. The concentration simulation was carried out for each of the segments, using the last concentration of the former segment as the initial concentration of the succeeded segment. The supposed ventilation pattern was upward displacement flow. This pattern is shown in figure 7.

The result of the simulation is shown in figure 2 a. The simulated concentration changes were about 50 ppm higher than the measured changes in the earlier two thirds of the measured period in both of the regions. In the later one third of the period, the simulated concentration approached to the measured concentration. This deviation might be caused by the assumption, that the ventilation rate was constant through the lecture. But the ventilation rate was less in the beginning and more in the end of the lecture. Because the main ventilation force was the temperature difference between the classroom and the corridor . The temperature difference was smaller in the beginning, and was larger in the end of the lecture. The vertical difference in the concentration changes in the two regions was well simulated by the equations.

The simulation result of the measurement on Nov. 18, 1986 is shown in figure 3. The ventilation rate was assumed to be 129 cub.m/h. The halves of it were assumed to ventilate the occupied and overhead regions, respectively. The simulated concentration change in the occupied region traced the measured concentration change well. The concentration change in the overhead region was about 100 ppm lower than the measured change in the middle of the measurement period. The following two reasons might concern to this deviation. One reason was that the fraction of ventilation was larger than 50 % for the overhead region. The other reason was that the supposed upward air stream was less than the practical value.

The simulation results deviated from the measured values as mentioned above. The classroom had not a mechanical ventilation system, so the exact ventilation rate could not be known. However, the calculations simulated the vertical difference in the carbon dioxide concentration reasonably. It was shown to be reasonable to assume that the occupant produced carbon dioxide was transported into the overhead region, then it diluted in this region. Also it was shown to be reasonable to assume that the plume flow above the occupants contributed to mix the air vertically.

5 RELATION BETWEEN VERTICAL CARBON DIOXIDE DISTRIBUTION AND LOCATION OF VENTILATION OPENINGS

When carbon dioxide is firstly mixed into an overhead region, and when it is mixed into an occupied region by the air interchange between the regions, a timely delay is caused in the concentraion rise in the occupied region. So the concentration rises in the two regions show differnece, even if the steady state concentrations in the two regions are equal. This difference appears clearly in a classroom, because the carbon dioxide concentration decreases during a break.

The same classroom, which was used for the experiment, was chosen for the following simulation subject. The influence of the plume flow on carbon dioxide distribution was examined for the following four patterns of ventilation opening locations. a) upward displacement ventilation, b) downward displacement ventilation, c) upper part cross ventilation, d) lower part cross ventilation. The air flow patterns are schematically shown in figures 7 to 10. The ventilation rate was supposed to be 16.3 cub.m/h·person. The supposed numbers of occupants were 13, 26 and 52 persons. The outdoor carbon dioxide concentration was 400 ppm.

The concentration changes in the upward displacement flow is shown in figure 7. The difference in concentration between the overhead and occupied regions increased with time. This difference became 160 ppm for the case of occupants of 52, and became to 140 ppm for the case of occupants of 13 after 60 min. from the start of lecture.

Figure 8 shows the changes in concentration in downward displacement ventilation. The concentration in the occupied region was the highest in this pattern. But the concentration was lower in the occupied region than in the overhead region in the beginning of lecture even in this flow pattern.

The concentration changes in the upper part cross ventilation are shown in figure 9. The concentration difference between the overhead and occupied regions was about 50 ppm in the first 30 min. for all the three numbers of occupants. This difference decreased with time. The difference was about 50 ppm after 60 min. in the case of occupants of 13. The difference almost disappeared at this time in the case of occupants of 52. The concentration in the overhead region of this flow pattern was almost same to that of the upward displacement ventilation. The concentration in the occupied region was higher in the upper part cross ventilation than in the upward displacement ventilation. The difference between the overhead and occupied region concentrations became larger, when the room volume per occupant decreased, or the occupation period prolonged.

Figure 10 shows the concentration changes in the lower part cross ventilation. In this flow pattern, the concentration in the occupied region changed almost equally to the downward displacement ventilation. The concentration in the overhead region was the highest in the lower part cross ventilation. The concentration in the occupied region in this flow pattern was almost same to that of the upper part cross ventilation.

When number of occupants was 13, the concentrations in the occupied region at 60 min. from the start of lecture were 1110, 1200, 1160 and 1180 ppm, respectiveley for upward displacement, downward displacement, upper part cross and lower part cross ventilations. When number of the occuapnts was 52, these values changed to 1550, 1720, 1700 and 1710 ppm. These values indicate that upward displacement ventilation was the most effective pattern. The second effective pattern was the upper part cross ventilation. This flow pattern is especially advantageous when a number of occupants is small (or a room volume per occupant is large), and the occupation time is short.

6 CONCLUSIONS

The following points were found in the experiments and in the simulation.

1. Definite vertical difference existed in the carbon dioxide concentration in the classroom.
2. This difference was caused by the fact that the expired air flowed upward by its thermal buoyancy and that it was transported by the temperature plume above the body.
3. Further, the plume influenced on the mixing of carbon dioxide in the classroom.
4. The vertical difference in the carbon dioxide concentration could be simulated by the modified two region ventilation model, which included the temperature plume flow as the air interchange between the two regions.
5. The lowest concentration in the occupied region was found in the upward displacement ventilation. The upper part cross ventilation is advantageous next to this flow, when a classroom is used intermittently.

REFERENCES

[1] Murakami, S. Tanaka, T. and Kato, S. 1983."Numerical simulation of air flow and gas diffusion in room model - correspondence between numerical simulation and model experiment." 4th Intern. Symp. on the Use of Computers for Environmental Engineering Related to Buildings, pp.90-95
[2] Pahm, Q.T. 1983."Generalized two-region model for infiltration studies." Building and Environment, vol.18, No.1/2, pp.55-60
[3] Skaret, E. and Mathisen, H.M. 1983."Ventilation efficiency-a guide to efficient ventilation." ASHRAE Transactions, vol.89 part 2 b, pp.480-495
[4] Pettenkofer, M. von 1858 "Uber den Luftwechsel in Wohngebauden." Literarisch-Artistische Anstalt, Munchen
[5] Houghten, F.C. and Blackshaw, J.L. 1933."Indices of air change and air distribution." ASHVE Transactions, vol.39, pp.261-276
[6] Yaglou, C.P. et al. 1937."Ventilation requirement." Heating, Piping and Air-conditioning, No.1
[7] Mierzwinski, S. 1980."Air motion and temperature distribution above a human body in result of natural convection." A4-series No.45, Inst. for Heat. and Ventil., Royal Institute of Technology, Stockholm, p.76
[8] Popiolek, Z. 1981."Problems of testing and mathematical modelling of plumes above human body and other extensive heat sources." A4-series No.54, Inst. for Heat. and Ventil., Royal Institute of Technology, Stockholm
[9] Grober, H.; Erk, S. and Grigull, U. 1961."Die Grundgesetze der Warme Ubertragung." Springer-Verlag, Berlin

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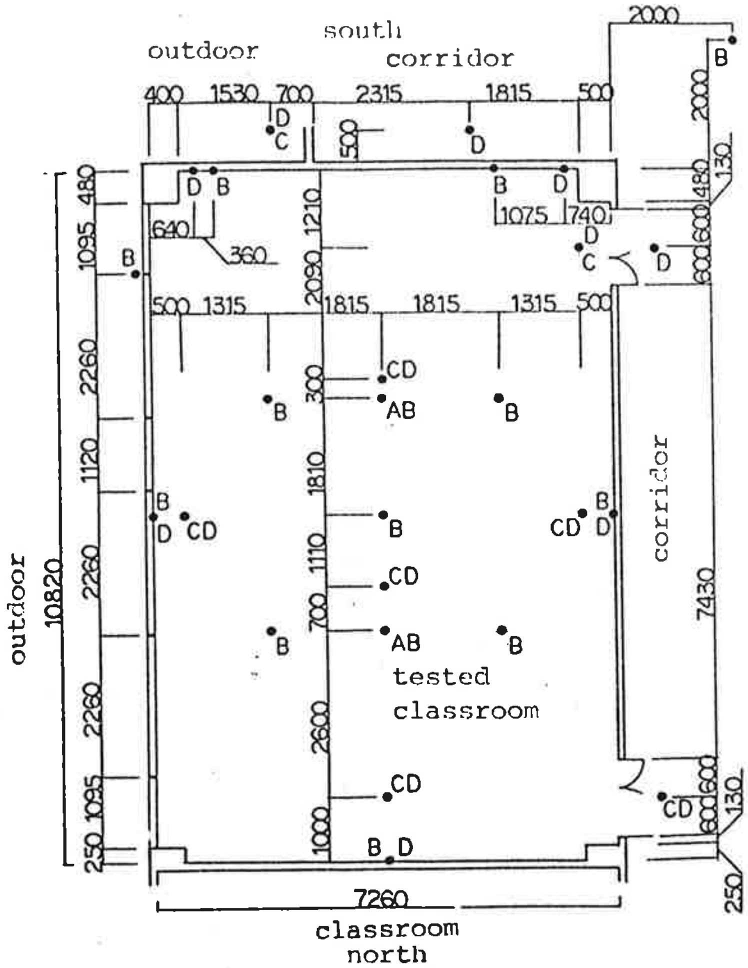


placement of measuring points

A : CO_2 concentration in 1985

B : temperature in 1985

C : CO_2 concentration in 1986

D : temperature in 1986

Fig. 1 Plan of Classroom for Measurement of Vertical Distribution of CO_2 and Placement of Measuring Points

Table 1 Conditions and Main Results of Carbon Dioxide Concentration Distribution Measurements in Classroom

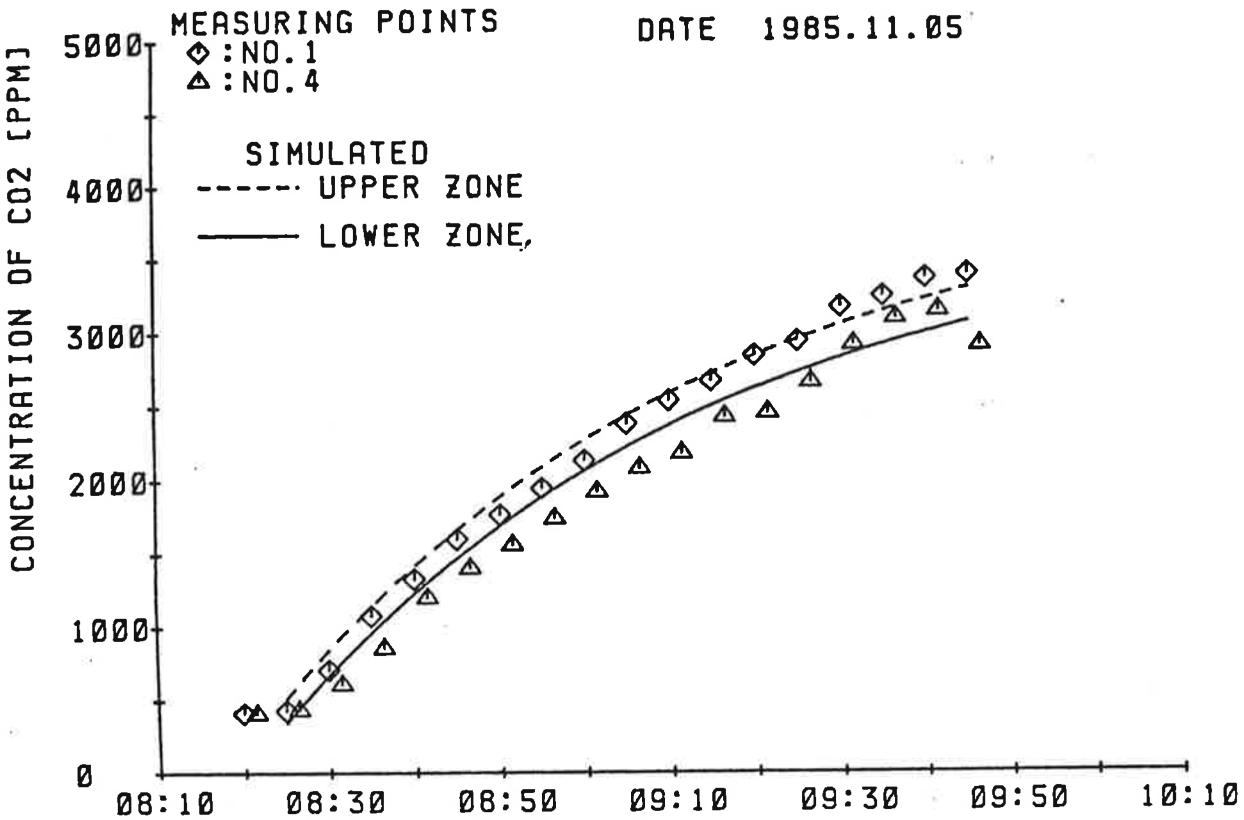
Date of Measurement	11-05	11-05	11-05	11-06	11-07	11-08	11-11	11-12	11-12	11-13	11-16	11-18	11-19	11-20	11-20	11-21	11-22
Start Time	08:25	13:30	15:05	14:55	08:30	13:30	08:25	13:30	14:50	14:55	10:35	08:25	08:25	08:30	13:35	13:35	15:05
End Time	09:40	14:45	16:10	16:10	09:25	16:05	08:50	14:40	16:30	16:20	11:05	09:40	09:40	09:40	16:00	16:30	16:10
Average(largest) Number of Occupants	43 (48)	51 (52)	47 (48)	48 (50)	43 (48)	51 (51)	43 (50)	49 (51)	43 (47)	50 (52)	16 (16)	15 (16)	18 (19)	13 (13)	17 (18)	9 (10)	8 (9)
Air Change Rate cub.m/h	310	268	190	401	516	307	138	299	1016	188	-----	50	73	122	45	156	-----
Air Change Rate per Occupant cub.m/h·p	7.2	5.3	4.1	8.4	12.0	6.1	3.2	6.1	23.7	3.8	-----	3.3	4.1	9.6	2.6	17.6	-----
Room Air Temperature *1 C	21.9	23,0	23.4	22.8	22.1	25.0	24.7	23.3	22.3	22.1	19.1	18.2	19.7	15.3	17.2	16.9	16.9
Outdoor Temperature C	16.9	18.4	17.1	17.8	18.4	21.1	16.3	15.4	14.2	13.1	11.5	11.8	10.6	8.2	12.0	14.9	16.5
Corridor Air Temperature C	17.6	18.2	17.6	18.3	18.4	21.8	17.5	17.3	20.9	15.0	13.5	13.0	12.9	12.0	14.8	16.1	16.0
Initial CO2 Concentration *2 ppm	447	1077	1883	820	593	697	537	1089	553	739	949	489	561	527	964	700	663
CO2 Concentration in Corridor ppm	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400	400
CO2 Concentration after 60 minutes *2 ppm	2985	3903	3937	3180	2480	3134	2089	3242	1360	3589	1877	1721	1817	1443	2401	1174	1272
Rise of CO2 Concentartion after 60 minutes *2 ppm	2538	2826	2053	2361	1887	2437	1552	2153	807	2849	928	1231	1256	915	1437	473	609
CO2 Concentration in Upper Region between 50 and 60 minute ppm	2869	3763	3873	3060	2412	3179	1859	3292	1475	3557	1778	1696	1808	1420	2392	1227	1324
CO2 Concentration in Lower Region between 50 and 60 minute ppm	2610	3603	3667	2816	2190	2695	1607	2880	924	3240	1630	1582	1578	1303	2144	1150	1175
Difference between Upper and Lower Concentration ppm	259	160	207	244	222	485	252	412	551	317	148	114	231	117	248	77	149
Wind Speed m/s	1.3	1.3	2.1	5.0	2.4	8.7	4.4	10.7	8.9	7.4	6.9	4.9	6.7	1.2	2.6	4.0	2.0
Wind Direction	NW	E	E	E	E	NW	NW	W	W	W	NW	NW	NW	W	W	W	W
Note																	

*1 average of 8 measuring points
*2 average of 8 measuring points in test room

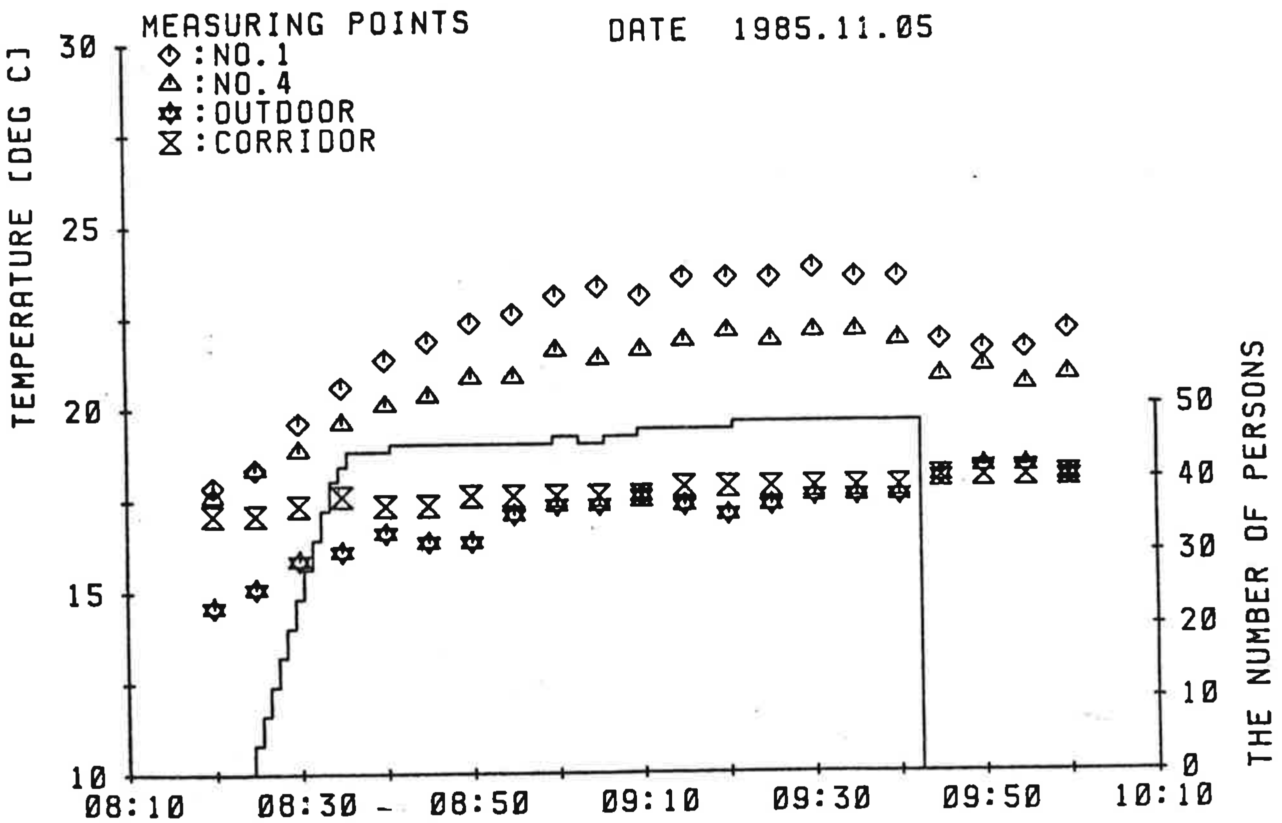
Table 2 Conditions and Main Results of Carbon Dioxide Concentration Distribution Measurements in Classroom

Date of Measurement	11-18	11-18	11-18	11-19	11-19	11-19	11-20	11-20	11-22	11-22	11-25	11-25	11-26
Start Time	08:10	11:15	13:15	08:30	10:00	13:10	08:15	09:50	09:40	11:20	11:25	13:20	12:55
End Time	09:50	12:00	14:45	09:50	11:00	15:00	09:30	11:10	11:10	12:30	12:15	14:10	14:00
Average(Largest) Number of Occupants	29 (50)	7 (7)	15 (18)	16 (16)	21 (25)	20 (23)	38 (49)	52 (52)	44 (51)	56 (56)	27 (35)	20 (23)	11 (12)
Air Change Rate cub.m/h	392	60	129	155	278	200	411	278	298	355	337	224	412
Air Change Rate per Occupants cub.m/h·p	13.6	8.9	8.6	10.0	13.3	9.9	10.7	5.4	6.7	6.4	12.7	11.3	36.0
Room Air Temperature *1 C	21.1	17.2	18.1	19.5	19.2	18.2	19.3	20.9	20.1	21.2	19.7	19.3	17.1
Outdoor Temperature C	12.0	14.5	15.2	11.8	13.1	15.1	10.0	13.1	14.1	15.7	18.5	18.6	11.8
Corridor Air Temperature C	13.7	15.1	16.1	13.7	13.8	16.2	13.3	14.4	14.13	15.9	17.7	18.2	13.7
Initial CO2 Concentration *2 ppm	728	618	984	552	952	544	720	2202	782	1288	552	684	508
CO2 Concentration in Corridor ppm	637	548	610	571	555	549	637	722	614	575	584	549	546
CO2 Concentration after 60 minutes *2 ppm	2626	1033	1940	1601	1833	1770	2621	4054	3162	3408	1787	1632	1032
Rise of CO2 Concentartion after 60 minutes *2 ppm	1898	416	956	1049	881	1226	1901	1852	2380	2119	1234	948	524
CO2 Concentration in Upper Region between 50 and 60 minute ppm	2725	1094	2033	1679	1979	1866	2616	3915	3123	3308	1951	1716	1058
CO2 Concentration in Lower Region between 50 and 60 minute ppm	2359	985	1763	1354	1673	1521	2358	3842	3035	3282	1748	1440	976
Difference between Upper and Lower Concentration ppm	365	109	270	325	306	345	259	73	88	26	203	276	82
Wind Speed m/s	2.1	3.3	3.5	4.0	6.7	6.6	1.2	2.6	7.5	8.2	5.7	8.8	12.1
Wind Direction	W	W	W	NW	W	W	NW	NW	NW	W	W	W	NW
Note													

*1 average of 15 measuring points
*2 average of 15 measuring points in test room



a. variation in carbon dioxide concentration



b. variation in temperature and number of occupants

Fig. 2 Measured and Simulated Variations in Carbon Dioxide Concentration in Classroom average No. of occupants 43, transoms open

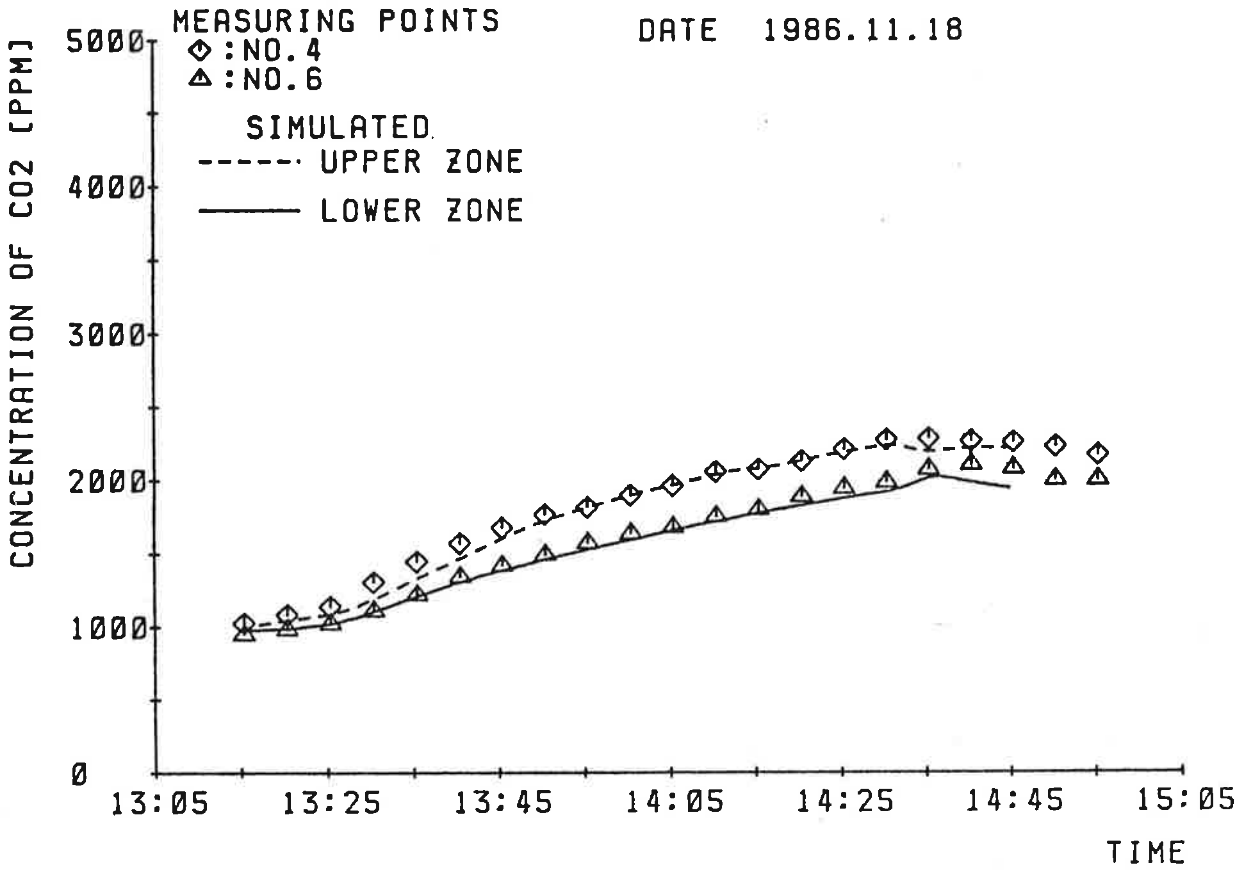


Fig. 3 Measured and Simulated Variations in Carbon Dioxide Concentration in Classroom average No. of occupants 15, transoms closed

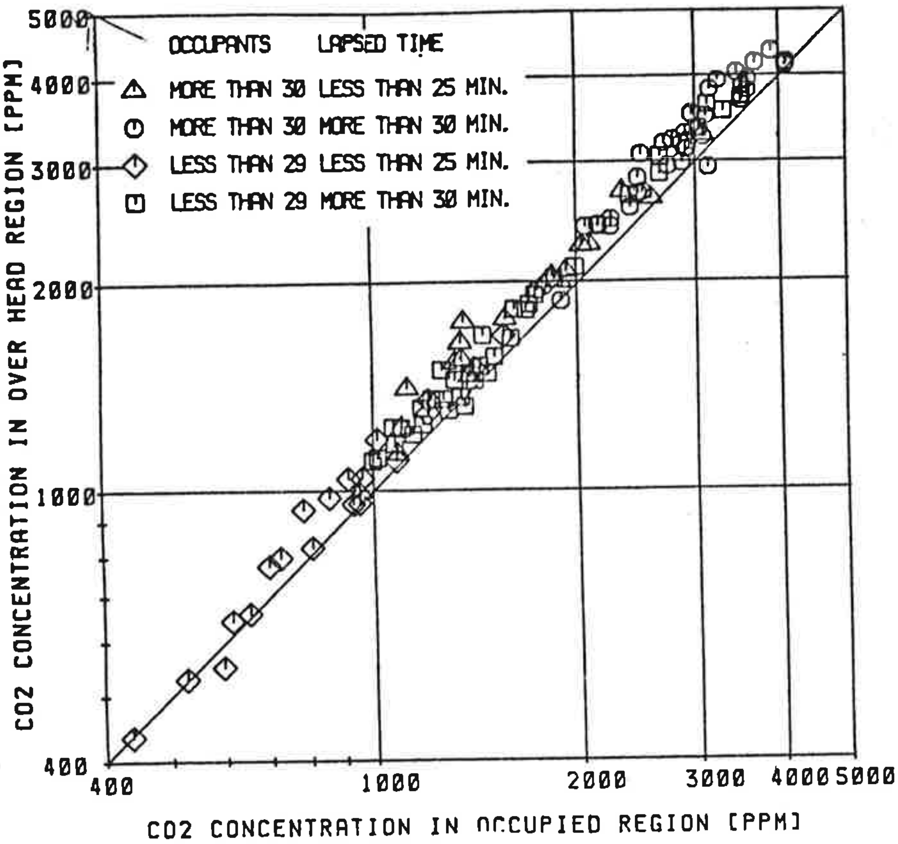


Fig. 4 Relations of Carbon Dioxide Concentration at Upper and Lower Measuring Points in Classroom, Transoms open, measured in 1985

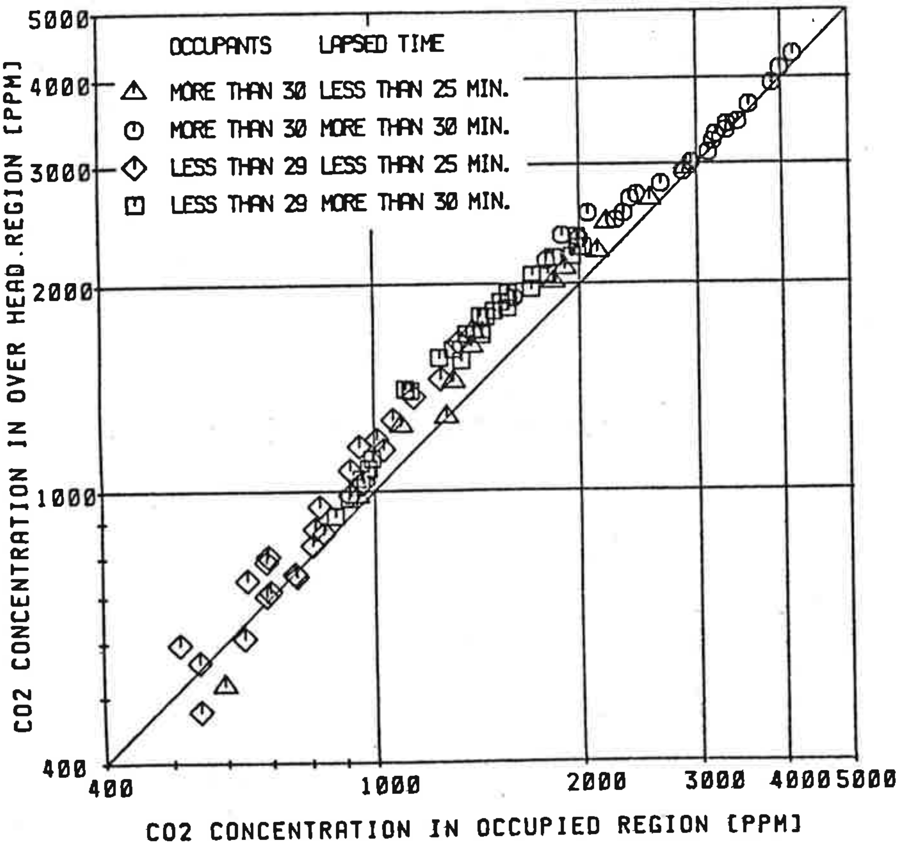
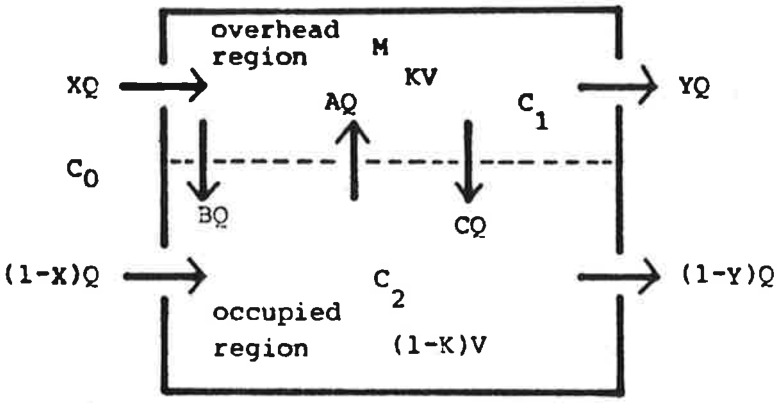


Fig. 5 Relations of Carbon Dioxide Concentration at Upper and Lower Measuring Points in Classroom, Transoms closed, measured in 1986



C_1 : pollution concentration in overhead region

C_2 : pollution concentration in occupied region

C_0 : pollution concentration in outdoor air

Q : ventilation rate
X : fraction of Q entering overhead region
Y : fraction of Q leaving overhead region
AQ : plume flow above occupants
BQ : down draught along walls
CQ : balance of flows
V : room volume
K : fraction of V of overhead region
M : pollution production rate

Fig. 6 Air Flow in Modified Two Region Ventilation Model

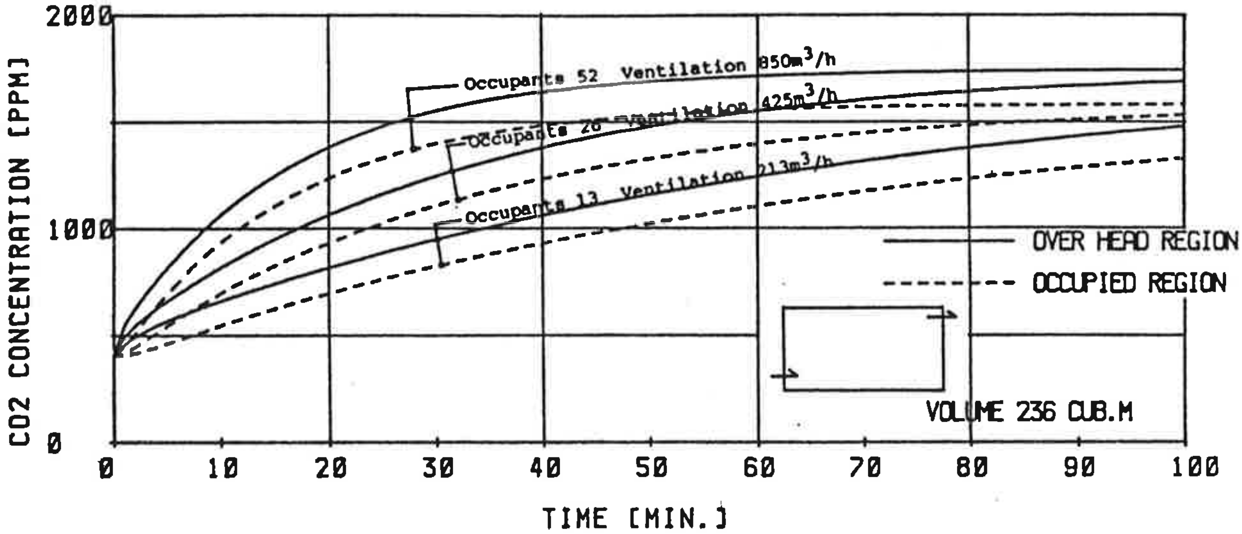


Fig. 7 Simulated Variations in Carbon Dioxide Concentration in Upper and Lower Regions in Classroom with Upward Displacement Ventilation

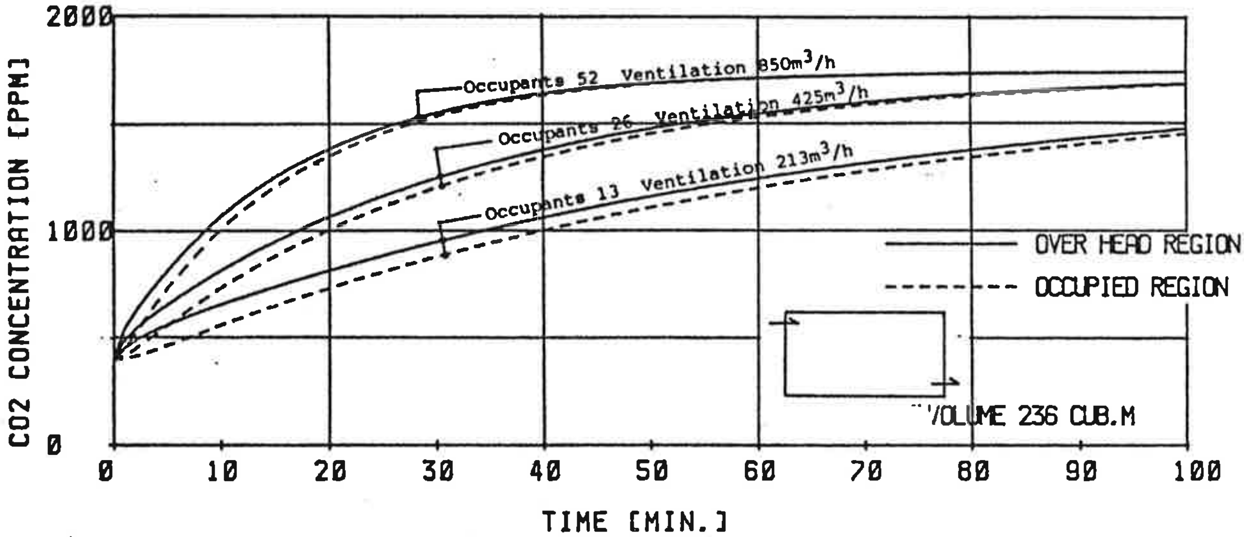


Fig. 8 Simulated Variations in Carbon Dioxide Concentration in Upper and Lower Regions in Classroom with Downward Displacement Ventilation

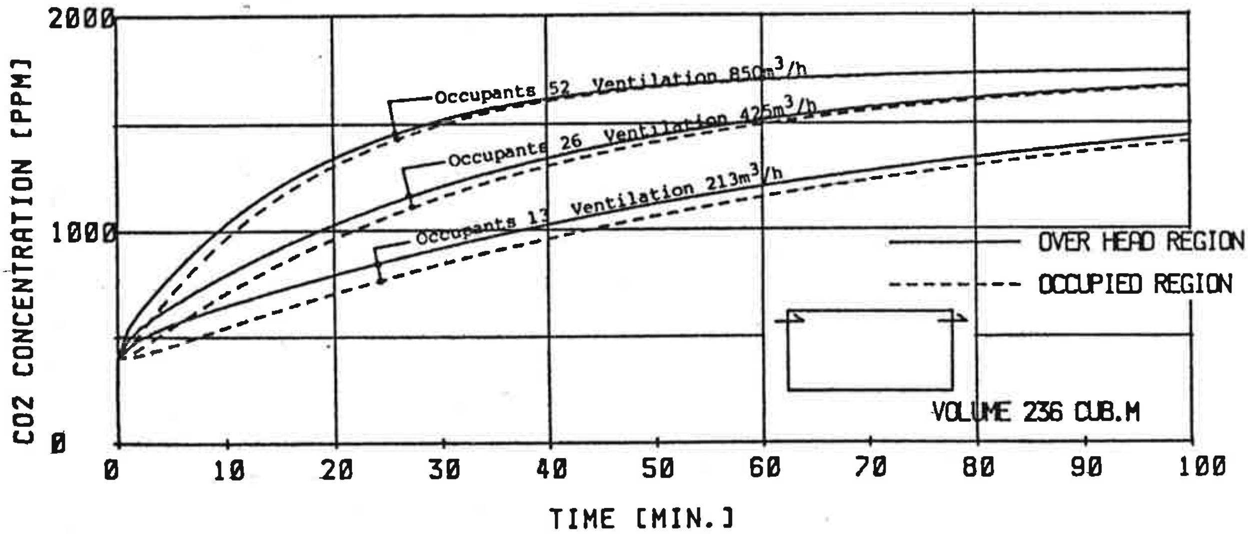


Fig. 9 Simulated Variations in Carbon Dioxide Concentration in Upper and Lower Regions in Classroom with Upper Part Cross Ventilation

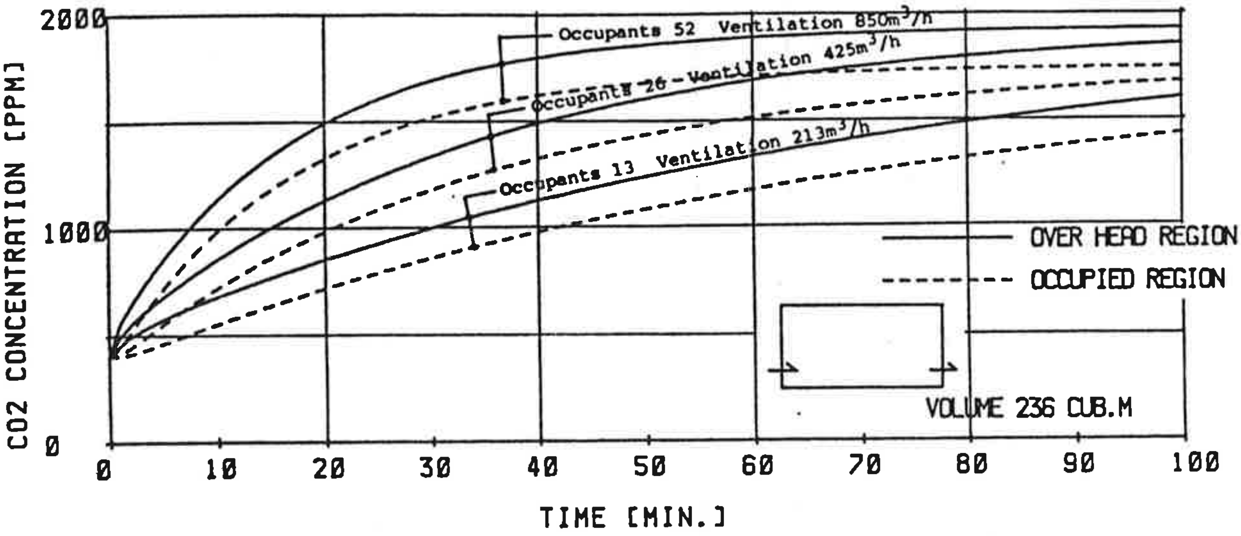


Fig. 10 Simulated Variations in Carbon Dioxide Concentration in Upper and Lower Regions in Classroom with Lower Part Cross Ventilation