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A study of a control strategy utilizing outdoor air to reduce the wintertime carbon dioxide levels in a typical Taiwanese bedroom

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Abstract

A CO_2 concentration of more than 1000 ppm has been monitored in Taiwanese bedrooms during sleeping hours in the wintertime. The high indoor CO_2 levels were caused by poor ventilation due to insufficient ventilation rates. This study sought to reduce the wintertime CO_2 concentration level in a typical Taiwanese bedroom with less outdoor air to maintain thermal comfort. CO_2 was used as an indicator to assess whether an adequate ventilation rate has been obtained to dilute or remove harmful pollutants. With the help of the thermal buoyancy effect, the CO_2 generated in the bedroom was effectively removed by means of less outdoor air. Through computational fluid dynamics simulations, the appropriate window and transom locations with the corresponding outdoor air supply volume, as well as the lowest possible outdoor air temperature were identified. © 1998 Elsevier Science S.A. All rights reserved.

Keywords: Ventilation; Indoor air quality; Thermal buoyancy; Outdoor air

1. Introduction

1.1. Background

Ventilation is needed to provide fresh air for metabolism, to maintain good indoor air quality for hygiene, and to produce a cooling effect for thermal comfort. Natural ventilation is defined as a flow through intentional and unintentional openings driven by wind and thermally (stack) generated pressures. Natural ventilation, an energy conservation design strategy, has long been used to control indoor thermal comfort [1]. Much of the design interest in natural ventilation arises from a desire to supplement or replace mechanical cooling rather than to provide indoor pollution control [2]. Very limited work has been undertaken on natural ventilation as a strategy to improve indoor air quality. The common approach in this area begins with the premise that adequate air quality will be achieved if the appropriate ventilation rates of certain standards, e.g., ASHRAE 62-1989, are supplied [2]. The indoor flow field and distribution of concentration of pollutants needs to be investigated if adequate air quality is required in a specific region.

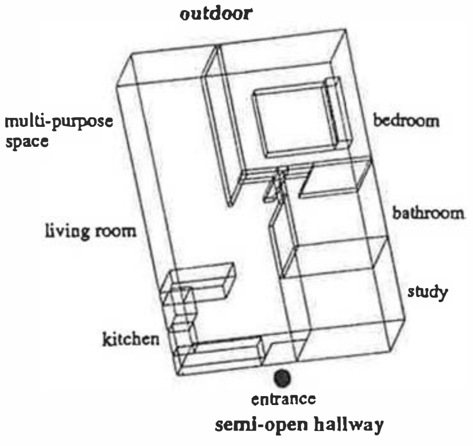

Fig. 1. Apartment unit.

Field measurements and wind tunnel tests are frequently used techniques in research related to building ventilation. Begun in the late 1970s, the employment of computational fluid dynamics (CFD) techniques in building ventilation has increased since the late 1980s [3]. Compared to the conventional experimental approaches, CFD techniques are less expensive, more flexible for simulating various boundary conditions, and capable of providing detailed information of flow fields. Turbulence models are always required in CFD simulations to approximate the turbulence phenomenon in

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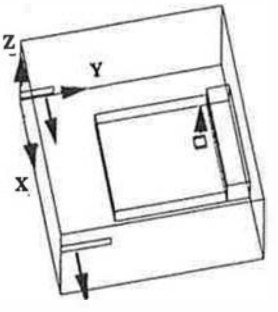

Fig. 2. Overall air-flow design pattern.

room flows. Therefore, the employed turbulence model should be validated by experimental data before being used as a research or design tool.

1.2. Statement of the problem

Carbon dioxide (CO_2) is produced as part of the human metabolism. The rate of production is fairly well defined and is dependent on the level of metabolic activity. The health and toxicity implications of carbon dioxide have been reviewed by Michael Hodgson, MD, of the University of Connecticut Health Sciences Center. His research indicates that, despite largely untested reports to the contrary, there is no physiological evidence that has any metabolic influence at concentrations below about 8500 ppm. For normal conditions of occupancy, however, measured CO_2 concentrations significantly above 1000 ppm provide an indication of inadequate ventilation for comfort and may mean that the ventilation rate is inadequate to dilute other, more harmful, pollutants that may be present. Therefore, the monitoring of CO_2 concentration can make a valuable contribution to the assessment of indoor air quality [4].

The indoor environments of twenty apartments selected from the northern, central and southern regions of Taiwan were examined. The wintertime CO_2 concentrations in the bedrooms and outdoors of these apartments were monitored for a 24-h period [5,6]. The results indicated that the average CO_2 concentration during bedtime for the twenty cases was 687 ppm, which exceeded the outdoor concentration (414 ppm) by 273 ppm. There were two cases in which the average CO_2 concentrations were over 1000 ppm, the ASHRAE recommended value. The increased indoor CO_2 concentrations indicates poor ventilation which is inadequate to dilute other pollutants.

Table 1
Simulation cases for bedrooms

Type	BA					BB	BC	BD	Bdh	BE	BF	BG
Case	BA-1	BA-2	BA-3	BA-4	BA-5	BB-1	BC-1	BD-1	BDh-1	BE-1	BF-1	BG-1
ach[a]	0.5	1	3	4	5	3	3	3	3	3	3	3
inlet velocity (m/s)	0.032	0.063	0.19	0.253	0.317	0.19	0.095	0.095	0.081	0.095	0.095	0.095
inlet area (m^2)	0.18	0.18	0.18	0.18	0.18	0.18	0.36	0.36	0.42	0.36	0.36	0.36
outlet area (m^2)	0.27	0.27	0.27	0.27	0.27	0.36	0.27	0.36	0.36	0.27	0.27	0.36

[a] Number of air changes per hour based on volume of bedroom.

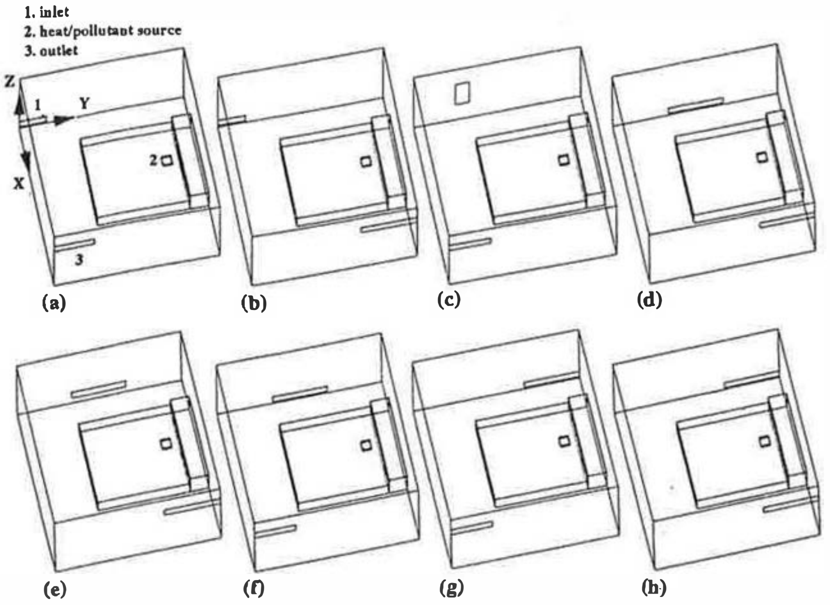

Fig. 3. Eight sets of cases: (a) BA, (b) BB, (c) BC, (d) BD, (e) BDh, (f) BE, (g) BF, and (h) BG.

Table 2
Dimensions and locations of openings and furniture

Dimension (m)	X	Y	Z	Location[a] (m)	X	Y	Z
space	3.8	3.6	3.0	inlet of BA, BB	0.	0.	0.1
inlet of BA, BB	0.	0.6	0.3	inlet of BC	0.	0.9	0.9
inlet of BC	0.	0.3	1.2	inlet of BD, BE	0.	1.2	0.1
inlet of BD, BE	0.	1.2	0.3	inlet of BDh	0.	1.2	0.3
inlet of BDh	0.	1.2	0.35	inlet of BF, BG	0.	2.4	0.1
inlet of BF, BG	0.	1.2	0.3	outlet of BA, BC, BE, BF	3.8	0.	2.1
outlet of BA, BC, BE, BF	0.	0.9	0.3	outlet of BB, BD, BDh, BG	3.8	2.4	2.1
outlet of BB, BD, BDh, BG	0.	1.2	0.3	bed	0.7	1.2	0.
bed	1.9	2.0	0.5	bed board	0.7	3.2	0.
bed board	1.9	0.4	0.8	heat/pollutant source	1.55	2.8	0.65
heat/pollutant source	0.2	0.2	0.1				

[a] Measured from origin to lower left corner of each object, viewed from direction of outlet.

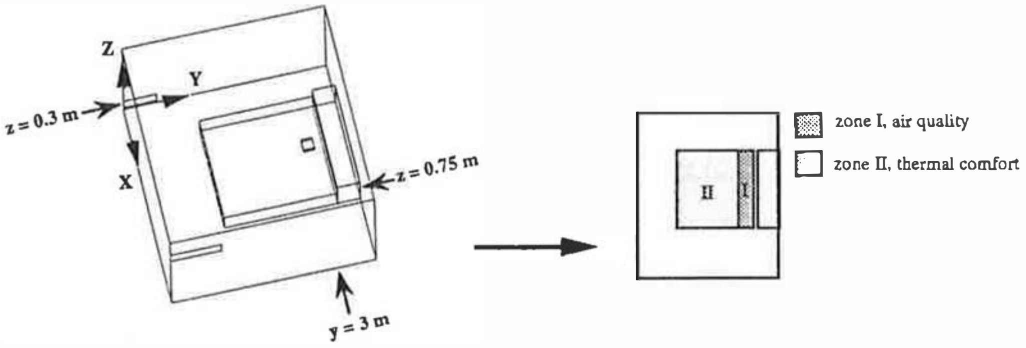

Fig. 4. Zones for evaluation.

Table 3
Impacts of various ach's

Type	BA				
Case	BA-1	BA-2	BA-3	BA-4	BA-5
ach*	0.5	1	3	4	5
thermal comfort (PMV)	0.075	0.044	−0.073	−0.105	−0.116
draft risk (%)	0.071	0.064	0.405	1.648	1.983
C_{out}[a] (ppm)	35 235.	17 760.	6145.	4502.5	3605.
C_{br}[b] (ppm)	18 930.	3360.	645.	1040.	1150.
ventilation efficiency (C_{out}/C_{br})	1.861	5.285	9.514	4.334	3.137

[a] C_{out} = average CO_2 concentration at outlet.
[b] C_{br} = average CO_2 concentration in breathing region.

In a typical Taiwanese bedroom space, only one wall is situated with a window for ventilation. During bedtime in winter, either a closed door or a closed window is desired to maintain indoor thermal comfort. Seven bedrooms in the twenty cases had their windows and doors closed during sleeping hours. The average CO_2 concentration of the seven bedrooms was 696 ppm. Twelve bedrooms had either a closed window or a closed door. The average CO_2 concentration of the twelve bedrooms was 699 ppm. Only one bedroom had an opened window and door, and its average CO_2 concentration was 486 ppm.

1.3. Objective of this study

Since bedrooms are designed for sleep, during which time the resting body repairs many systems, it is important, for the purpose of health, in the ventilation design of bedrooms that an adequate ventilation rate is supplied. This study uses CO_2 as an indicator to assess whether an adequate ventilation rate has been obtained to dilute or remove harmful pollutants. For the purposes of better indoor air quality and energy conservation, this study seeks to reduce the wintertime CO_2 concentration levels in Taiwanese bedrooms by means of outdoor

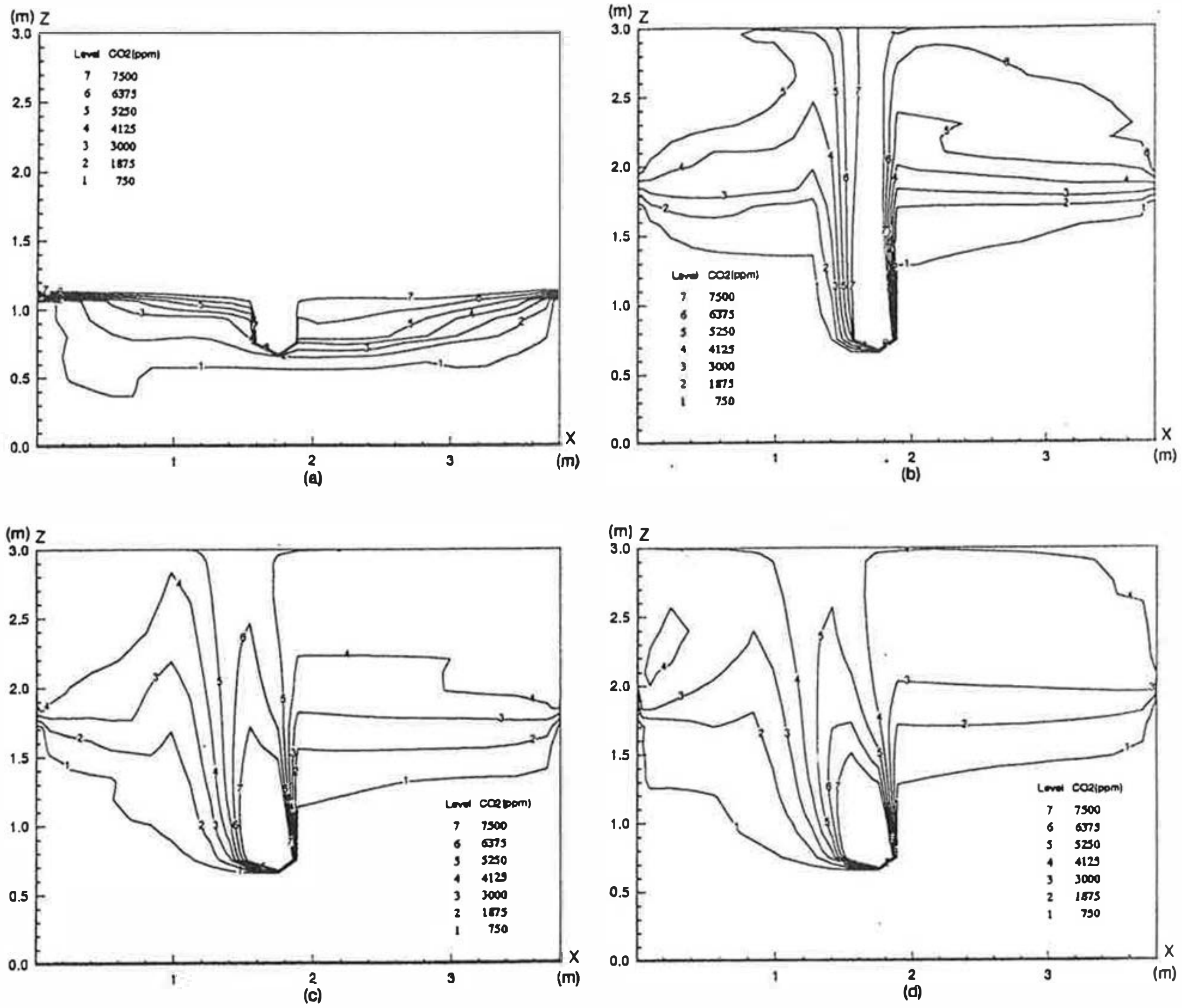

Fig. 5. Distribution of CO_2 at $y = 3.0$ m for cases: (a) BA-2, (b) BA-3, (c) BA-4, and (d) BA-5.

air. To maintain indoor thermal comfort, the effective removal of the CO_2 generated by sleeping persons by means of less outdoor air is emphasized. To achieve this goal, the appropriate window and transom locations with the corresponding outdoor air-supply volume and lowest possible outdoor temperature are suggested. The required outdoor air-supply volume can be driven indoors by a fan when the natural driving force is insufficient.

2. Approach

2.1. Control strategies

One bedroom space was chosen from an apartment unit (Fig. 1) in an apartment complex located in Taipei. This apartment unit was one of the twenty cases investigated by Chiang et al. [6]. The occupant of this apartment is a single female. During bedtime when the measurements were taken, the window and the door of the bedroom were closed. The average CO_2 concentration in this bedroom was 591 ppm, which was higher than that in the exterior (350 ppm) by 241 ppm.

To facilitate the effective removal of CO_2, the thermal buoyancy effect is employed as the main control strategy. The thermal buoyancy phenomenon is generated in the form of a thermal plume when a heat source is present in a relatively colder and still ambient air. When driven by the buoyancy effect, the air and pollutants in a plume move upward. In this way pollutants generated by heat sources can be removed effectively with a small amount of supplying air [7].

2.2. Design parameters

To make the removal of CO_2 possible, an overall air-flow design pattern based on the thermal buoyancy effect is suggested (Fig. 2). An inlet (window) and outlet (transom) are required to complete this overall air-flow pattern. During sleeping hours the door of the bedroom is considered closed.

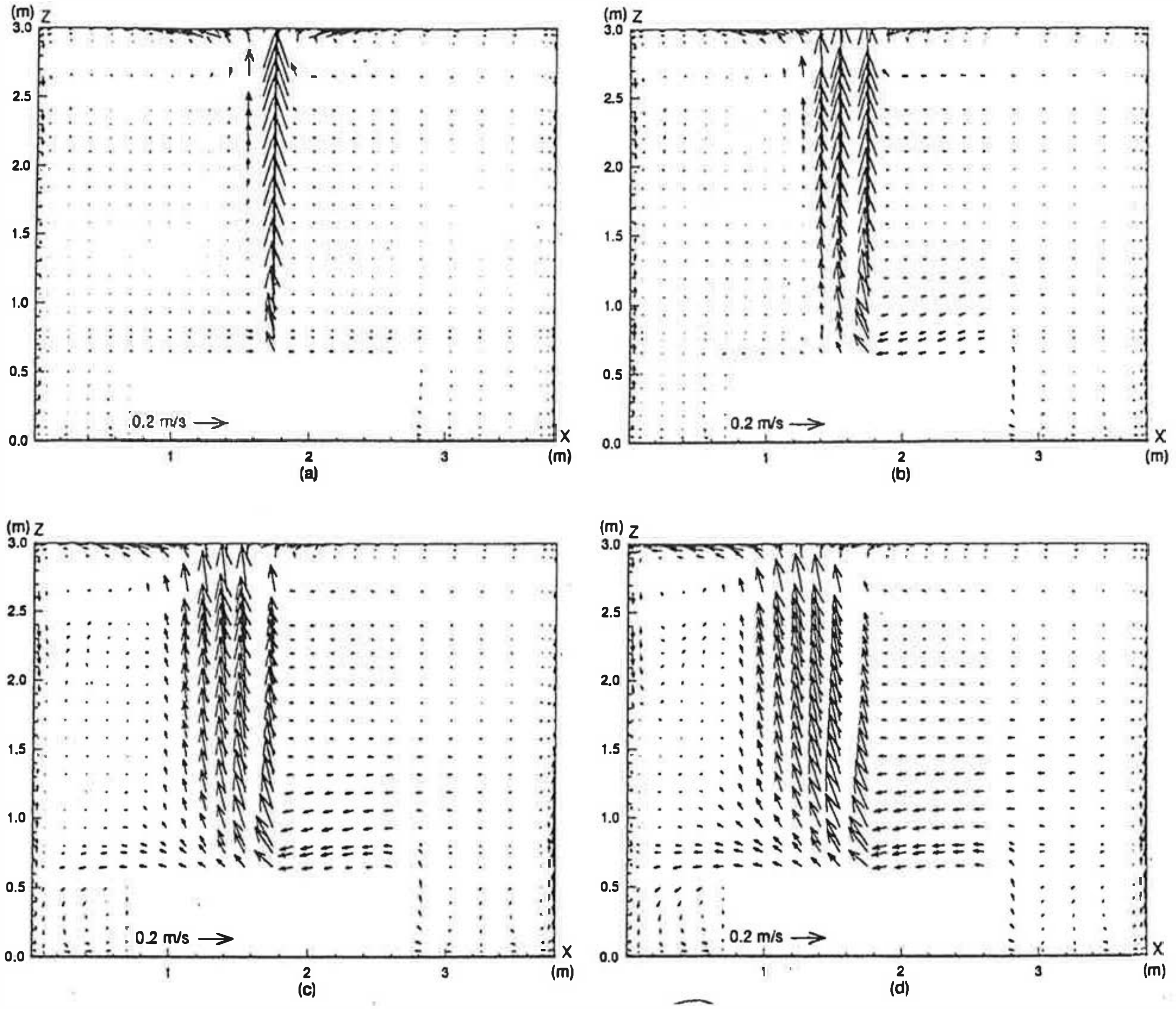

Fig. 6. Flow field at $y = 3.0$ m for cases (a) BA-2, (b) BA-3, (c) BA-4, and (d) BA-5.

The examined design parameters are the locations of the window and transom, the outdoor air supply volume, and the outdoor temperature. To evaluate various design parameters for the effectiveness of CO_2 removal and indoor thermal comfort, twelve cases are examined (Table 1 and Fig. 3) by several computational fluid dynamics simulations.

2.3. Computational fluid dynamics simulation

The domain and the dimensions of the simulations are shown in Table 2. The heat source generates a heat flux of 75 W/m^2, equal to two persons sleeping. The CO_2 emission rate from this heat source is 2.0×10^{-4} m^3/s, equal to the amount exhaled by 50 persons. The room temperature, 17°C, was considered 2°C higher than the outdoor temperature. All simulations were conducted in three dimensions in $28 \times 28 \times 28$ cells. All walls were treated as adiabatic.

With the present capacity and power of computers, turbulence models are often required in the computational fluid dynamics simulations to make the conservation equations solvable. Most turbulence models are developed for specific flows. Therefore, a turbulence model may work excellently for one case but poorly for another. The turbulence model applied in this study is the renormalization group k-ε model [8] which is more advanced in predicting the thermal buoyancy effect [9] than the standard k-ε model [10] and the modified k-ε model [11]. The renormalization group k-ε model has the same form as the standard k-ε model, except for the model coefficients. The model coefficients in the renormalization group k-ε model are:

$$(\delta_k, \delta_\varepsilon, C_{1\varepsilon}, C_{2\varepsilon}, C_\mu) = (0.7194,\ 0.7194,\ 1.42,\ 1.68,\ 0.0845) \tag{1}$$

In addition, the dissipation-rate transport equation has an additional source term R:

$$R = \frac{C_\mu \eta^3 (1 - \eta/\eta_0)}{1 + \beta \eta^3} \frac{\varepsilon^2}{k} \tag{2}$$

where $\eta_0 = 4.8$, $\beta = 0.012$ and the dimensionless parameter, η, is defined by:

Table 4
Impacts of different outlet locations

Set	I		II		III	
Case	BA-3	BB-1	BE-1	BD-1	BF-1	BG-1
ach*	3	3	3	3	3	3
thermal comfort (PMV)	−0.073	−0.072	−0.102	−0.253	−0.125	−0.123
draft risk (%)	0.405	0.363	0.082	0.085	0.169	0.170
C_{out}[a] (ppm)	6145.	7972.5	6352.5	7895.	6292.5	7867.5
C_{br}[b] (ppm)	645.	945.	95.	115.	157.5	222.5
ventilation efficiency (C_{out}/C_{br})	9.514	8.446	67.118	68.143	40.133	35.533

[a] C_{out} = average CO_2 concentration at outlet.
[b] C_{br} = average CO_2 concentration in breathing region.

Table 5
Impacts of various horizontal window locations

Type	BA	BE	BF
Case	BA-3	BE-1	BF-1
ach*	3	3	3
thermal comfort (PMV)	−0.073	−0.102	−0.125
draft risk (%)	0.405	0.082	0.169
C_{out}[a] (ppm)	6145.	6352.5	6292.5
C_{br}[b] (ppm)	645.	95.	157.5
ventilation efficiency (C_{out}/C_{br})	9.514	67.118	40.133

$$\eta=S\frac{k}{\varepsilon},\ S=(2S_{ij}S_{ij})^{1/2},\ S_{ij}=\frac{1}{2},\ S_{ij}=\frac{1}{2}(U_{i,j}+U_{j,i})$$

The computations are conducted by PHOENICS [12], a commercially available CFD code, which is widely used among ventilation engineers. This code has several routines accessible to users. Therefore, users are able to modify the codes according to their needs. The governing equations are solved by the finite-volume method with a staggered grid system. A hybrid scheme is used for the numerical solution. The algorithm employed is SIMPLEST [12]. As a convergence criterion, the sum of the normalized absolute residuals in each control volume for all calculated variables should be less than 10^{-3}. To prevent the numerical solution process from oscillating or diverging, three methods are used: (1) under-relaxation for the continuity equation, (2) false time-steps for the other dependent variables, and (3) source-term manipulation which treats positive source terms explicitly and negative source terms implicitly. A non-uniform mesh system is used with denser meshes in the near-wall regions or the places where a large gradient of variables is present.

2.4. Evaluation models

To assess the performance of each design option, indoor thermal comfort and the indoor CO_2 concentration are two criteria to be evaluated. Indoor thermal comfort is evaluated on both fanger's predicted mean vote [13] and his draft risk model [14]. The predicted mean vote is determined by three personal parameters and four environmental parameters. The three personal parameters are metabolism, external work, and clothing insulation; the four environmental parameters are air temperature, mean radiant temperature, mean air velocity, and partial water vapor pressure. The draft risk model is a function of mean air velocity, turbulence intensity, and air temperature. To obtain a 90% level of satisfaction in thermal comfort, the value of the pmv should be kept between −0.5 and +0.5. A 15% or lower level of dissatisfaction in draft risk is desirable.

Indoor air quality is evaluated on both the average CO_2 concentration in the breathing zone and the relative ventilation efficiency [15]. A low CO_2 concentration and a high relative ventilation efficiency in the breathing zone indicate an effective removal of CO_2. The relative ventilation efficiency in an evaluated region is expressed as:

$$\bar{E}_r=(c_x-c_e)/(\bar{c}-c_e) \tag{4}$$

where c_x is the contaminant concentration in the exhaust air (ppm), c_e is the contaminant concentration in the outdoor air supply (ppm), and $\bar{c}$ is the mean contaminant concentration in the evaluated region (ppm).

The mean PMV value (thermal comfort index) in region II and the average CO_2 concentration in region I are evaluated (Fig. 4). The PMV value is calculated in an air layer (region II) which is located above and across the entire bed. The dimensions of this air layer are 2.0 m × 1.9 m × 0.15 m (length × width × height). The considered metabolic rate for a sleeping person is 35 kcal/h m^2. A thick cotton comforter is the bedding frequently used in Taiwan during winter. Since the thermal properties of the thick cotton comforter were unavailable, they were assumed to be 3.0 for the clothing resistance (Icl) and 1.4 for the clothing property (fcl). The CO_2 concentration is evaluated in the breathing zone (region I), which surrounds the source. The dimensions of this region are 1.9 m × 0.5 m × 0.15 m (length × width × height).

3. Results and discussion

3.1. Volume of outdoor air supply

This section investigates the influences of the volume of the outdoor air supply on the effectiveness in removing CO_2

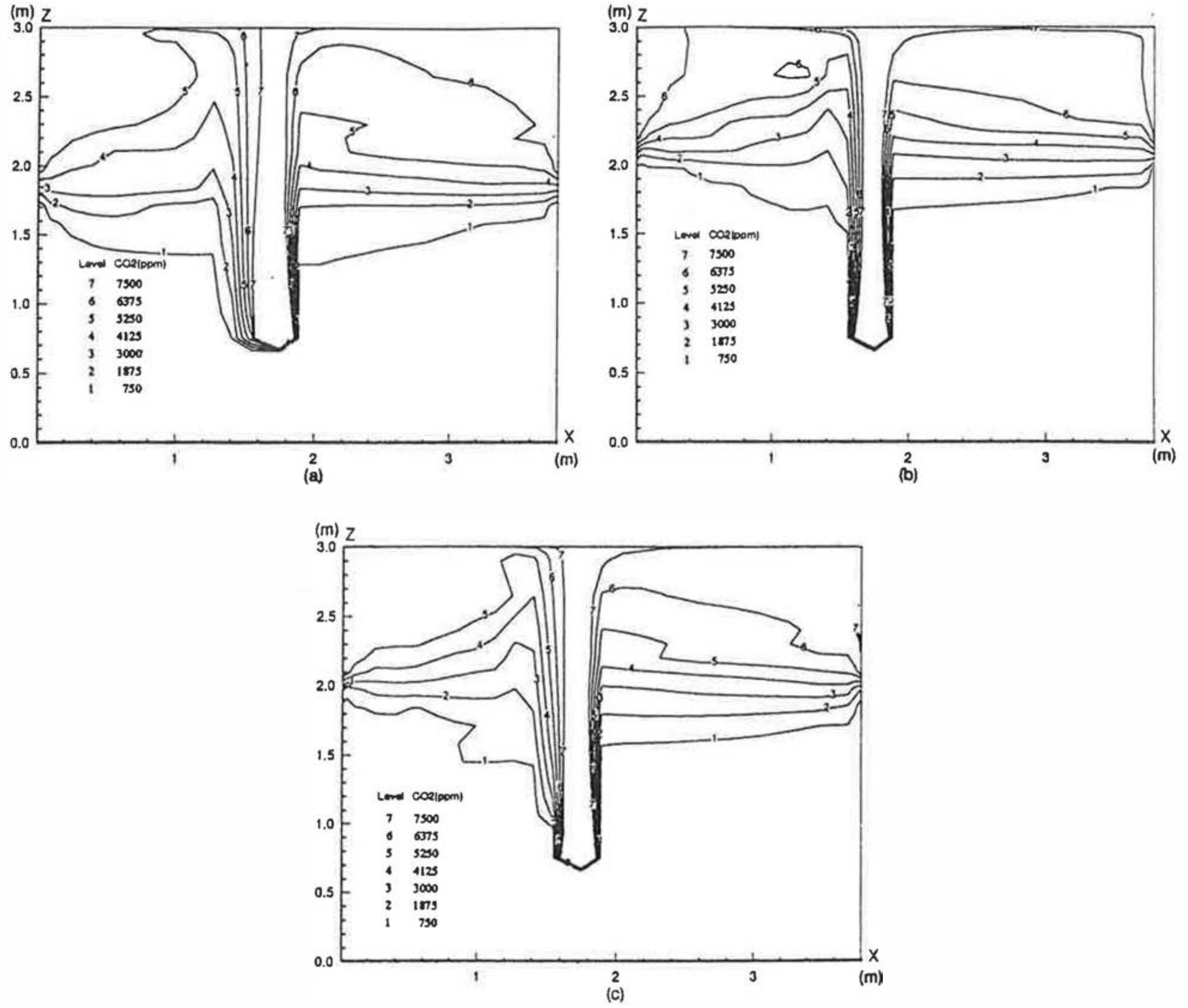

Fig. 7. Distribution of CO_2 at $y = 3.0$ m for cases (a) BA-3, (b) BE-1, and (c) BF-1.

from the bedroom and the indoor thermal comfort. The volume of the outdoor air supply is expressed by the number of air changes per hour (abbreviated ach). Five cases of type BA (Fig. 3) with varying ach's from 0.5 to 5 are examined (Table 3).

From Table 3 one can observe that the average CO_2 concentration in the breathing region (C_{br}) decreases first and then increases with an increasing ach. The lowest average CO_2 concentration and the highest relative ventilation efficiency is reached at 3 ach. This indicates that an optimum air supply volume makes the removal of CO_2 from the breathing region effective. This phenomenon agrees with the previous research results on the mechanism of the thermal buoyancy effect induced by a displacement ventilation system [16–18]. It has been found that neither a small nor a large air supply volume is desirable in order to achieve a lower pollutant concentration level in an occupied zone.

When a small volume of outdoor air is supplied, the high CO_2 concentration in the breathing region is caused by an under-developed thermal plume in which the pollutants are unable to be transferred to an upper level. This situation can be observed by comparing Fig. 5a with b. In Fig. 5a the stratified contour lines are compact in the lower region, indicating an under-developed thermal plume. From Table 3 one can observe that the CO_2 concentration in the breathing region increases with an increasing ach when the volume of the air supply is larger than 3 ach. The increased CO_2 concentration is caused by a strong plume flow when a large flow rate is supplied to the heat source. This situation can be seen in Fig. 6, in which the plume size increases with an increasing air supply volume. Limited by the ceiling, the plume flow produces a reversed air stream to pull the pollutants in the higher region to a lower level. This phenomenon is pronounced when a strong plume is present. Compared with Fig. 5b, either

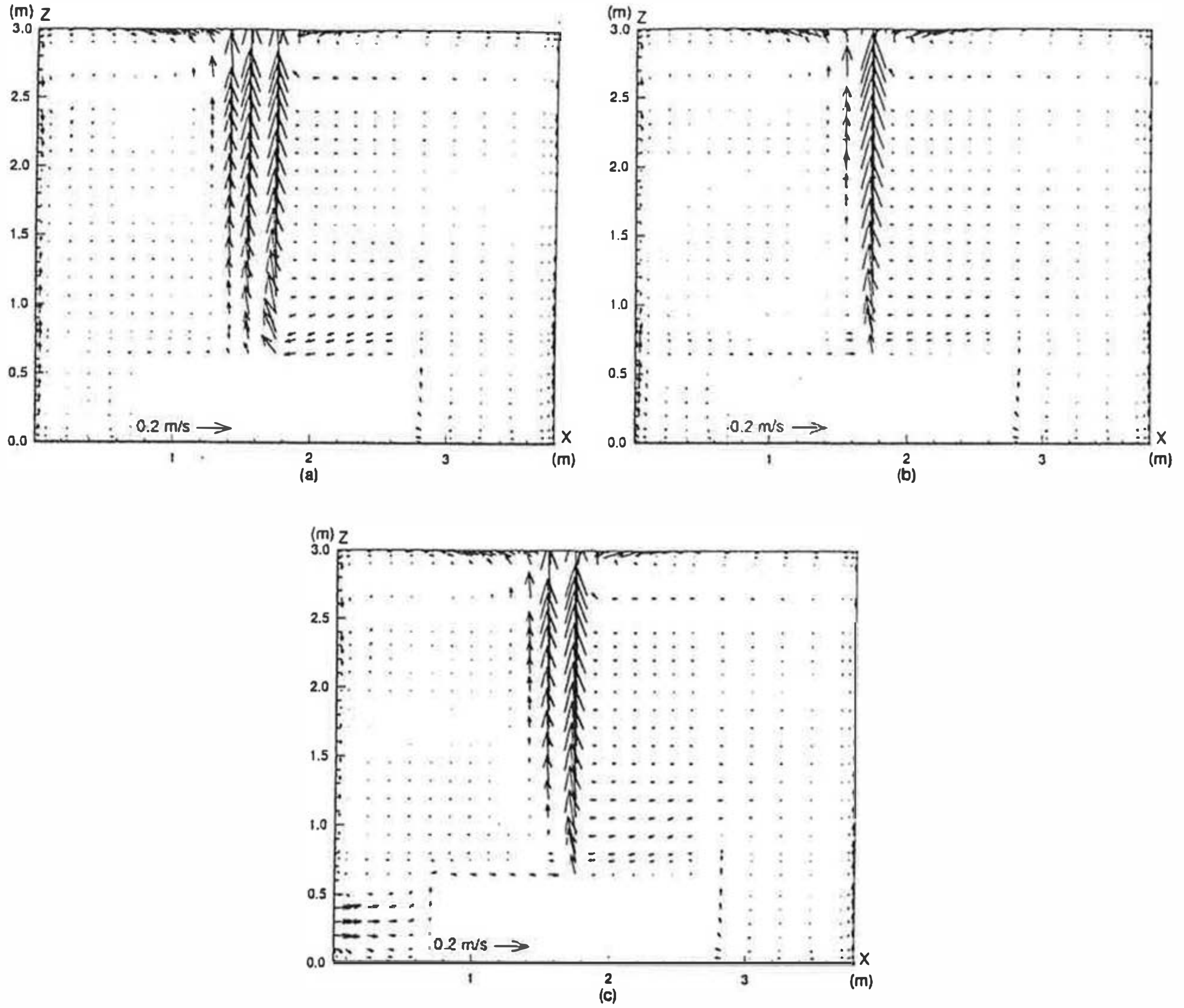

Fig. 8. Flow field at $y = 3.0$ m for cases (a) BA-3, (b) BE-1, and (c) BF-1.

Fig. 5c or d has fewer compact stratified contour lines and a lower position for each contour line. This indicates that the polluted region is enlarged, caused by more mixture between the pollutants drawn from the upper region and the clean air in the lower region.

The PMV value on the bed decreases with an increasing ach. For five cases a 90% level of satisfaction in thermal comfort was obtained. In five cases the percentages of dissatisfaction due to drafts are well below 15%, a desirable criterion.

3.2. Outlet location

This section investigates the influences of the outlet location on the effectiveness in removing CO_2 from the bedroom and the indoor thermal comfort. Three sets of inlet–outlet locations, in which three inlet locations and two outlet locations are examined, are shown in Table 4 and Fig. 3. For all six cases the considered air supply volume is 3 ach.

From Table 4 one can note that the CO_2 concentration in the breathing region for cases with a left outlet is always lower than that for cases with a right outlet. One can also observe that the CO_2 concentration at the outlet for cases with a left outlet is lower than that for cases with a right outlet. In each set the ventilation efficiency of the case with a left outlet is close to that with a right outlet. In addition, little differences are shown in the thermal comfort level and the draft risk between the two outlet locations. Therefore, the impacts from different outlet locations on the indoor thermal comfort level and the effectiveness in removing CO_2 can be neglected.

3.3. Horizontal window location

This section investigates the influences of the horizontal window location on the effectiveness in removing CO_2 from the bedroom and the indoor thermal comfort. Three different horizontal window locations are examined (Table 5 and Fig. 3). The left outlet location is considered in this investigation, in which the air supply volume is 3 ach.

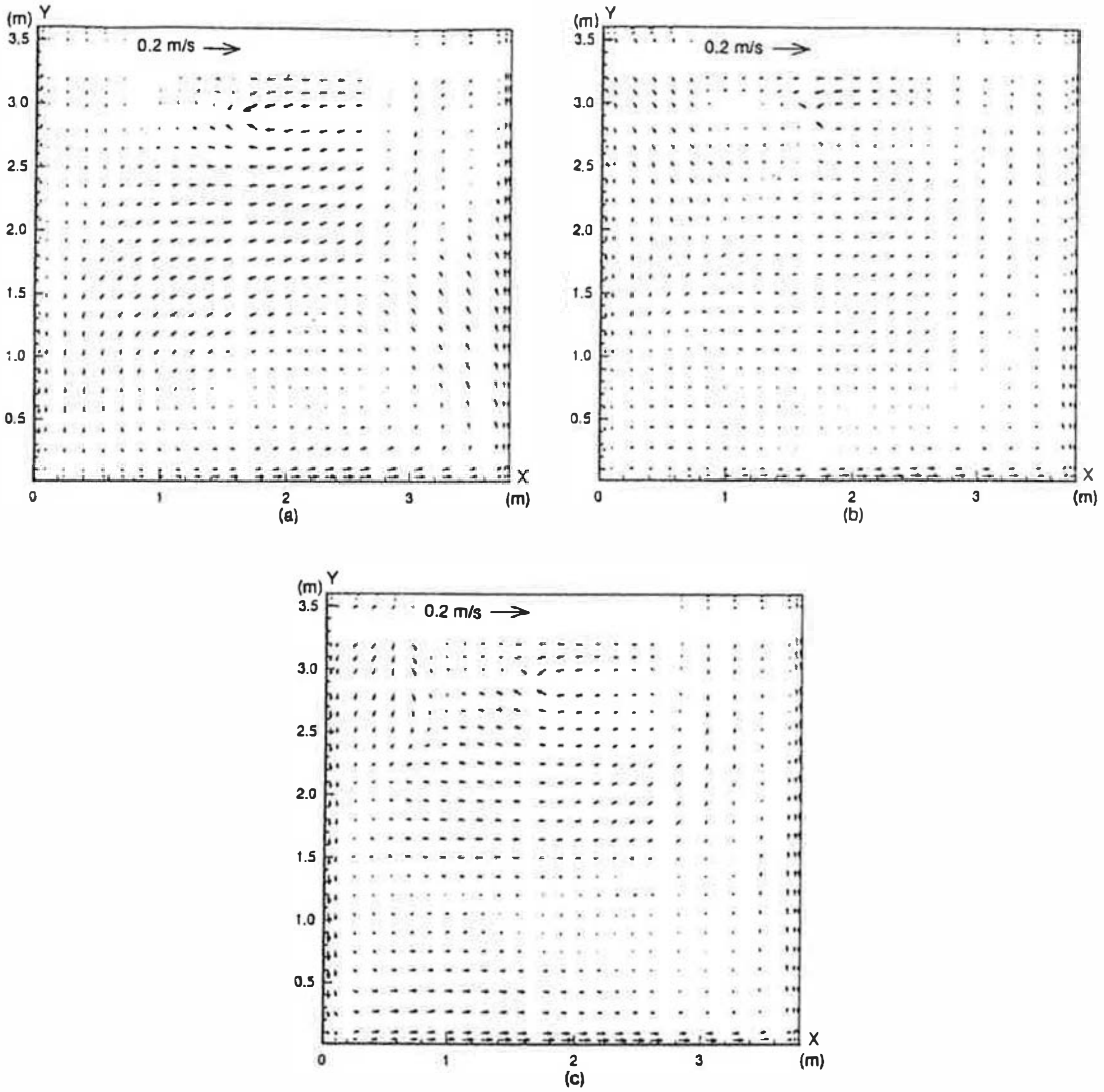

Fig. 9. Flow field at $z = 0.75$ m for cases (a) BA-3, (b) BE-1, and (c) BF-1.

From Table 5 one can observe that case BE-1 obtains the lowest level of CO_2 concentration in the breathing region. This situation can also be observed in Fig. 7. Compared with Fig. 7a and c, Fig. 7b (case BE-1) has the highest position of the stratified pattern of contour lines. The higher the pattern of contour lines, the lower the CO_2 concentration in the breathing region.

In Fig. 8 one can observe that case BA-3 (Fig. 8a) has the strongest plume flow, compared with cases BE-1 (Fig. 8b) and BF-1 (Fig. 8c). A stronger plume flow carries more pollutants from the upper region to the lower region. This phenomenon explains why case BA-3 has the lowest location of the pattern of contour lines and, consequently, the highest level of CO_2 concentration in the breathing region.

A stronger plume can be produced when a larger air flow rate is supplied to the heat/pollutant source. In Fig. 9one can observe that case BA-3 (Fig. 9a) has the longest velocity vectors in the vicinity of the heat/pollutant source, compared with case BE-1 (Fig. 9b) and case BF-1 (Fig. 9c). The longer velocity vector in case BA-3 represents more air supplied to the heat/pollutant source. In Fig. 10a (case BA-3) one can note that the supplying air stream from the inlet approaches the heat/pollutant source without being blocked by furniture. In Fig. 10b (case BE-1) one can observe that the supplying airflow from the inlet is divided into two streams when encountering the bed. Only the right stream reaches the heat/pollutant source. This situation explains why case BE-1 produces a weaker plume because of less air volume supplied to the heat/pollutant source.

On the basis of the aforementioned explanations, the CO_2 concentration level in the breathing region of case BA-3 can be lower when a lower volume (lower than 3 ach) of supply air is applied. From Table 6one can observe that a lower level of CO_2 concentration is obtained when the ach decreases to

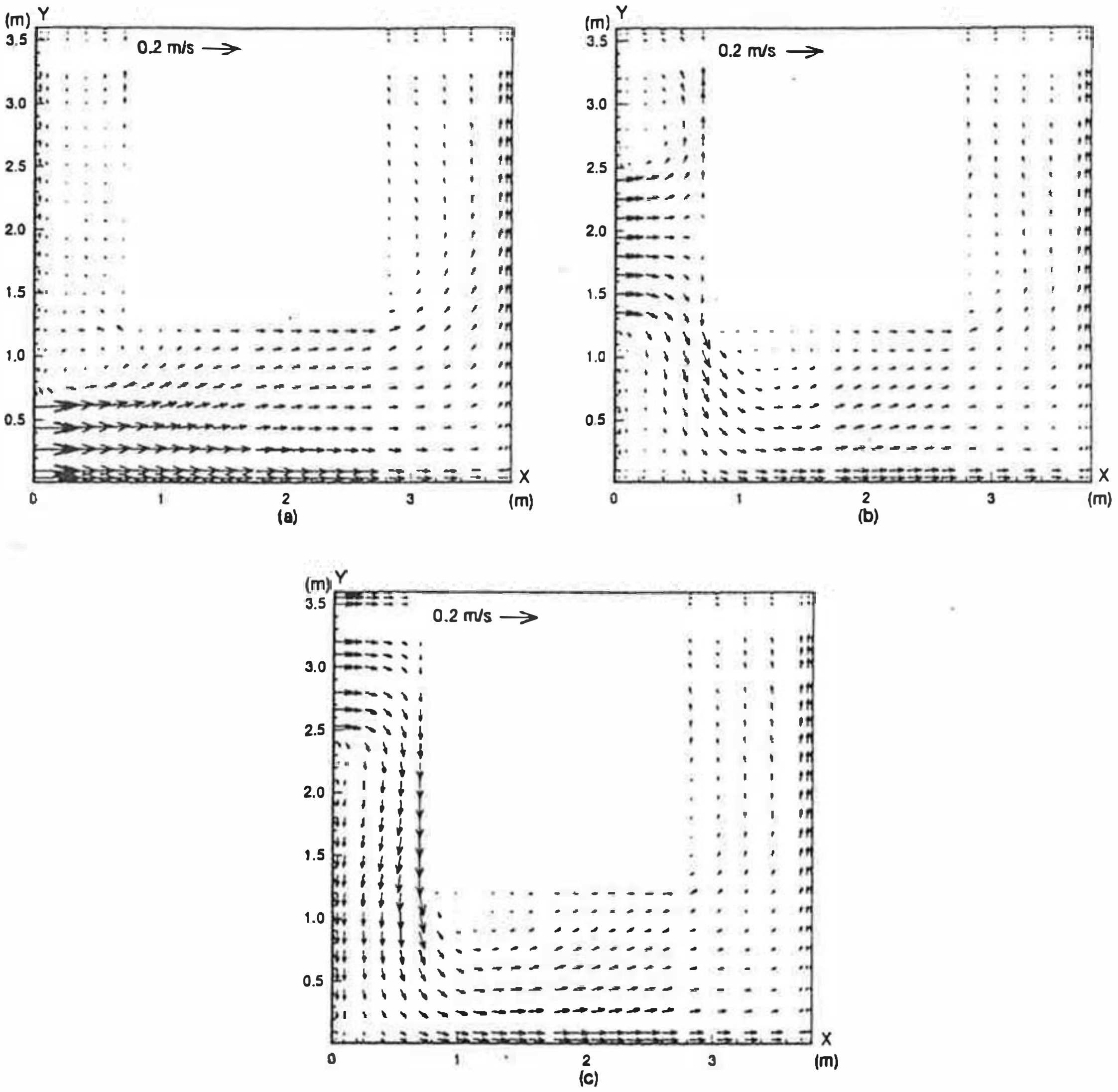

Fig. 10. Flow field at $z=0.3$ m for cases (a) BA-3, (b) BE-1, and (c) BF-1.

Table 6
Impacts of lower ach's

Type	BA		
Case	BA-3	BA-6	BA-7
ach*	3	2	1.5
thermal comfort (PMV)	−0.073	−0.018	0.013
draft risk (%)	0.405	0.083	0.067
C_{out}^{a} (ppm)	6145.	9075.	11 950.
C_{br}^{b} (ppm)	645.	217.5	737.5
ventilation efficiency ($C_{\text{out}}/C_{\text{br}}$)	9.514	41.646	16.203

2 ach. The optimum air supply volume to achieve the lowest level of CO_2 concentration in the breathing region could be within 2 and 3 ach or 1.5 and 2 ach.

For all three cases (Table 5) a 90% level of satisfaction in thermal comfort was obtained. In all three cases the percentages of dissatisfaction due to drafts are well below 15%, a desirable criterion. In Fig. 11, the distribution of PMV on the bed, one can observe that cases BE-1 and BF-1 have cooler regions at the left side of the bed near the head of the sleeping person. If thermal comfort in the bed is the main concern, case BA-3 would be preferred, although cases BE-1 and BF-1 obtained lower levels of CO_2 concentration in the breathing region.

3.4. Vertical window location

This section investigates the influences of the vertical window location on the effectiveness in removing CO_2 from the bedroom and the indoor thermal comfort. Two sets of cases are presented in which three different vertical window locations are examined (Table 7 and Fig. 3). The locations are lower than the bed (case BA-3 and case BD-1), higher than the bed and lower than the heat/pollutant source (case BDh-1), and higher than the heat/pollutant source (case BC-1). The left outlet location is considered in this investigation, in which the air supply volume is 3 ach.

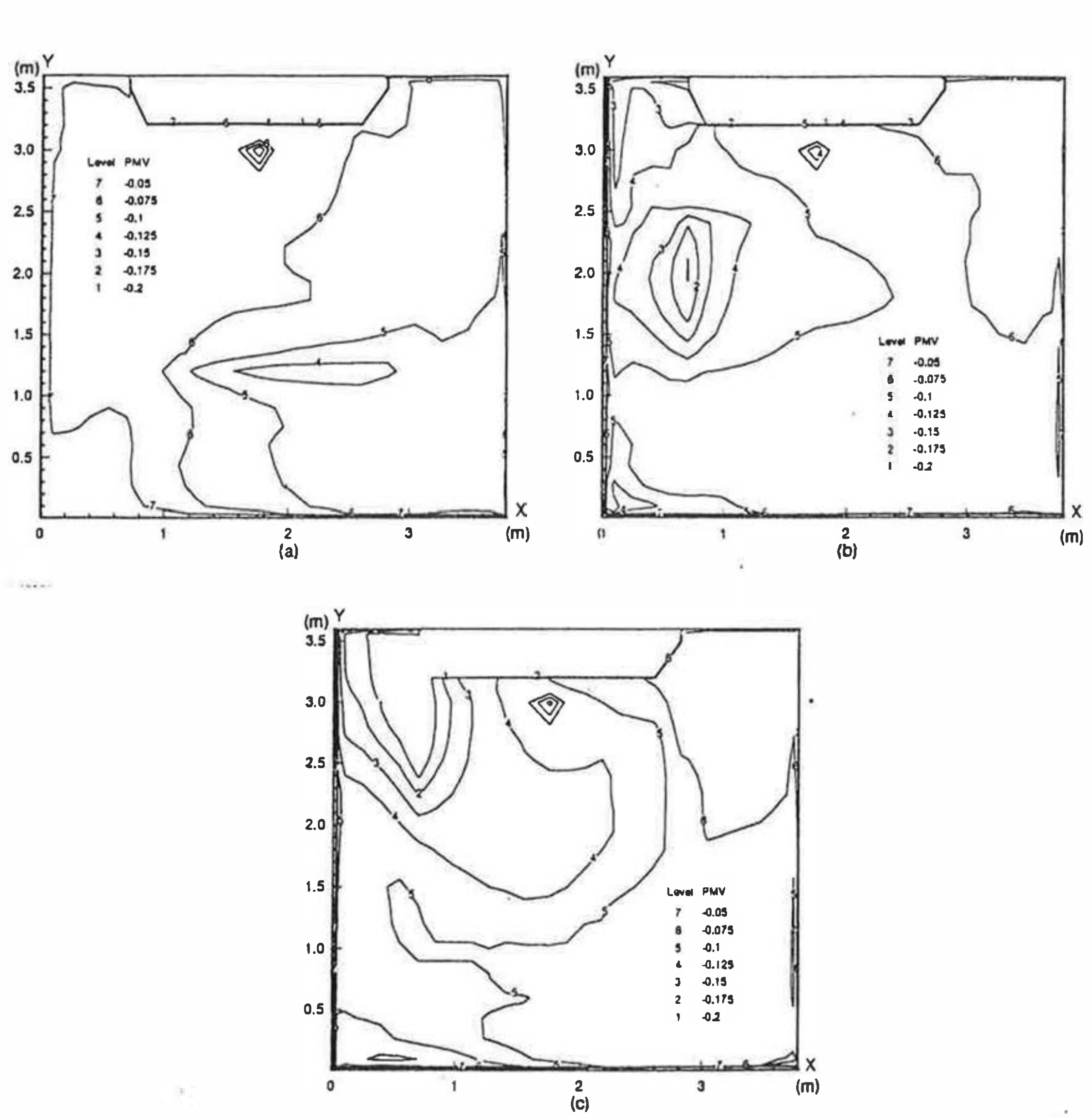

Fig. 11. Distribution of PMV at $z=0.65$ m for cases (a) BA-3, (b) BE-1, and (c) BF-1.

Table 7
Impacts of various vertical window locations

Set	I		II	
Case	BA-3	BC-1	BD-1	BDh-1
ach*	3	3	3	3
thermal comfort (PMV)	−0.073	−0.046	−0.253	−0.133
draft risk (%)	0.405	0.081	0.085	0.100
$C_{out}{}^{a}$ (ppm)	6145.	6002.5	7895.	7717.5
$C_{br}{}^{b}$ (ppm)	645.	1185.	115.	82.5
ventilation efficiency (C_{out}/C_{br})	9.514	5.066	68.143	93.248

In Table 7 one can observe that case BC-1 has the highest CO_2 concentration in the breathing region, compared with the other cases. This situation can be observed in Fig. 12. Compared with case BA-3 (Fig. 12a), case BC-1 (Fig. 12b) has its contour line 1 in a very low position which touches the floor and the bed. The descending contourline 1 indicates an increasing CO_2 concentration level in the breathing region. The high inlet location, higher than the heat/pollutant source, is the cause for case BC-1's obtaining a high level of CO_2 concentration in the breathing region. The supplying air flow from the high inlet location counteracts the growth of the thermal plume generated by the thermal buoyancy effect at a lower level near the heat/pollutant source. Therefore, the clean air supply mixes with the CO_2 generated from the source, rather than replacing it. This explains why no stratified contour lines are found under a height of 1.8 m in Fig. 12b.

From set II in Table 7 one can observe that case BDh-1 has a lower level of CO_2 concentration and a higher ventilation efficiency compared to case BD-1. Case BDh-1 has a higher inlet location which makes the air supply stream reach the heat/pollutant source more easily than in case BD-1. This is the cause for case BDh-1's having a lower level of CO_2 concentration in the breathing region. The higher window

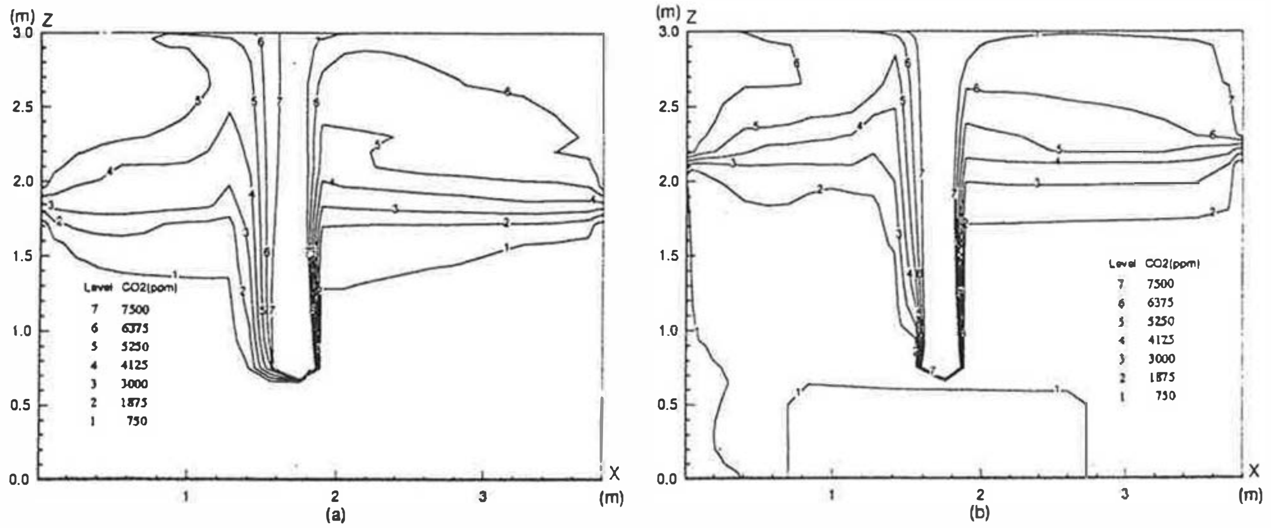

Fig. 12. Distribution of CO_2 at $y=3.0$ m for cases (a) BA-3 and (b) BC-1.

Table 8
Impacts of various outdoor temperatures

Case	BA-6					
outdoor temperature (°C)	10.	11.	12.	13.	14.	15.
indoor temperature (°C)	12.	13.	14.	15.	16.	17.
thermal comfort (PMV)	−0.872	−0.702	−0.531	−0.360	−0.189	−0.018
draft risk (%)	0.106	0.101	0.097	0.092	0.088	0.083

location is likely to cause a low temperature region in the bed when placed at the side of the window. To avoid any possible cold feeling in the bed, a lower inlet (lower than the bed) is preferred.

For all four cases a 90% level of satisfaction in thermal comfort was obtained. In all four cases the percentages of dissatisfaction due to drafts are well below 15%, a desirable criterion.

3.5. Outdoor temperature

This section examines the lowest possible outdoor temperature for maintaining an 80% level of satisfaction in thermal comfort (Table 8). Case BA-6 is considered in this investigation because of its better performance in removing CO_2 with less outdoor air. It was found that the lowest outdoor temperature for maintaining an 80% level of satisfaction in thermal comfort is 10°C.

4. Conclusions

The objective of this study was to utilize outdoor air to reduce the wintertime CO_2 concentration level in the bedroom of a typical Taiwanese apartment. CO_2 was used as an indicator to assess if an adequate ventilation rate was obtained to dilute or remove harmful pollutants. The key issue was to maintain indoor thermal comfort by the effective removal of CO_2 with less outdoor air. To facilitate the effective removal of CO_2, the thermal buoyancy effect was employed. Instead of mixing with the clean air supply, the thermal buoyancy effect causes the polluted air to be replaced by the clean air supply. Through an examination by computational fluid dynamics simulations, the appropriate window and transom locations with the corresponding air supply volume, as well as the lowest possible outdoor air temperature, were identified.

To conclude the bedroom design, three flow diagrams (Fig. 13) were used. Diagram A represents a favorable design (all cases except BA-1, BA-2, BA-4, BA-5 and BC-1) in which the thermal buoyancy effect is successfully activated and the polluted region is kept high in an upper level, away from the breathing region. Diagram B illustrates the situation of an enlarged polluted region (cases BA-4 and BA-5) when a stronger plume is present. The enlarged polluted region is caused by the strong reflected air stream produced from a strong plume flow when restricted by the ceiling. Diagram C

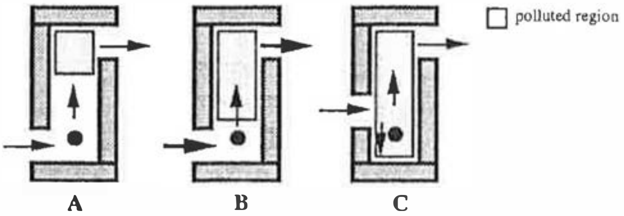

Fig. 13. Flow diagrams for bedroom design.

illustrates a traditional window location (case BC-1) in which the inlet location is higher than the heat/pollutant source, the sleeping person. Due to the high inlet location, the thermal stratification at a lower level generated by the thermal buoyancy effect is destroyed. Consequently, a higher level of CO_2 concentration is obtained in the breathing region, compared with cases with lower inlet locations. A different outlet location has a negligible effect on the indoor thermal comfort and the effectiveness in removing CO_2 from the bedroom. If thermal comfort in the bed is essential, the inlet should be positioned away from and lower than the bed.

With the help of the thermal buoyancy effect, CO_2 can be removed effectively with less outdoor air to maintain indoor thermal comfort. For type BA the optimum air supply volume to achieve the lowest level of CO_2 concentration in the breathing region could be within 2 and 3 ach or 1.5 and 2 ach. When the outdoor air supply volume is 2 ach, the lowest outdoor temperature to maintain an 80% level of satisfaction in thermal comfort is 10°C.

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