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Effects of Window Position on the Air Flow Distribution in a Cross-Ventilated Residential Bedroom

Key Words
Residences
Cross-ventilation

Abstract
Results of an investigation of the effects of window position on the airflow characteristics for a typical bedroom setting in Taiwan are presented. Four different window positions were examined in the experiment which used a full-scale laboratory bedroom model with a single bed. A three-dimensional ultrasonic anemometer was used to measure airflow distribution and the results of flow measurements at two height levels are presented. Computer simulation of the airflow distribution was performed using the standard k-ε turbulence model. The measurements and the computer calculations resulted in similar airflow distributions for all positions of window openings. Close congruence between the results of calculations and those of the measurements shows the validity of using such a computer simulation in the airflow design of a residential bedroom. The results also show that the positions of window openings have appreciable effects on the airflow distribution. Proper window position is therefore an important factor in the design of ventilation for a cross-ventilated bedroom.

Introduction

As stated by Fanger [1], the philosophy behind ventilation has been changing in the last 200 years. A study initiated by Yaglou et al. [2] in the mid 1930s stated that ventilation is also a factor for human comfort. Extensive evaluations and measurements by Chiang and Wang [3] found that the indoor air environment for housing in Taiwan should be a subject of further study. Indoor air quality problems in bedrooms were found to be especially severe. In the study of Chiang and Wang [3], measured carbon dioxide (CO_2) concentrations of above 1,000 ppm were noted when the windows of the bedrooms were closed. Chuah et al. [4] found that pollution sources generated indoors were the major problems for indoor air quality in residential buildings. It was pointed out by Chuah et al. [4] that the CO_2 concentration could reach well above 1,000 ppm if windows were closed during bedtime for a typical bedroom with single occupancy in Taiwan.

Chiang et al. [5] carried out further studies on the impacts of outdoor air and living behaviour pattern on the indoor air quality. The investigation was carried out using several city apartments as case studies. Solutions to the indoor air quality problem for housing were studied by Chao et al. [6] and improvements in air quality were demonstrated for changes in bedroom design.

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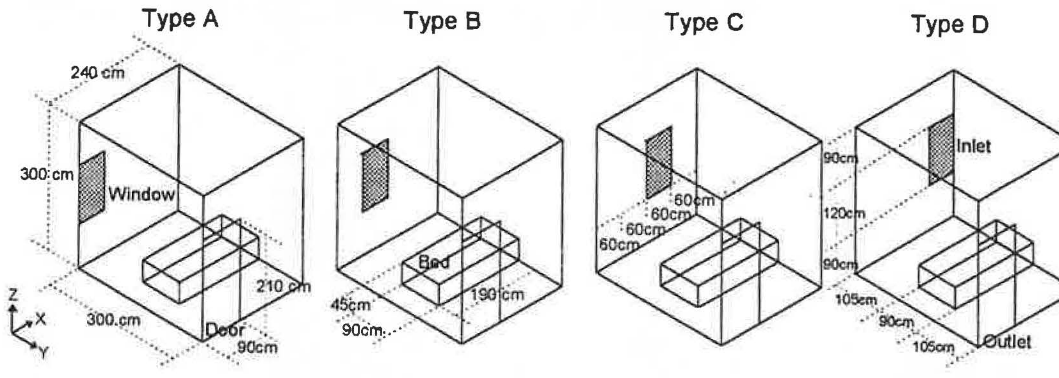

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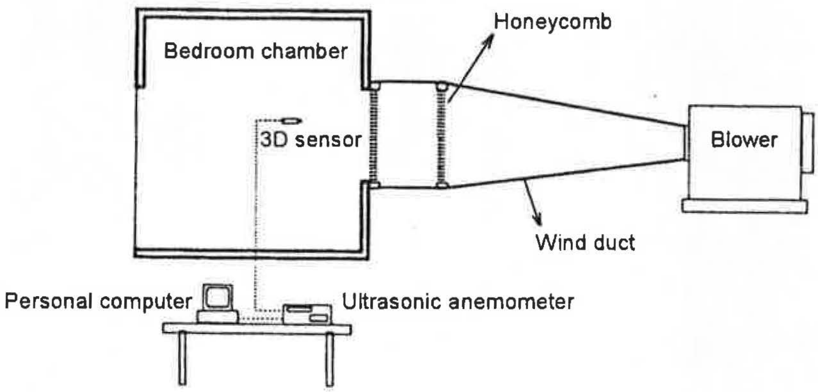

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Fig. 1. Perspective view of the laboratory bedroom model with four types of window openings.

Fig. 2. Schematic diagram of the experimental apparatus.

The climate of Taiwan is subtropical with average temperatures of 22 and 24.5 °C, respectively, for the northern and the southern regions of the island [7]. Based on the report of the Central Weather Bureau of Taiwan, the yearly average wind speed in open spaces is around 2 and 3 $m \cdot s^{-1}$ [8], and breezy conditions are the norm most of the time for housing areas. Window openings are therefore effective means of ventilation.

This study used a laboratory bedroom model to investigate the effects of the relative positions of the window openings on the airflow distribution. A natural cross-ventilated residential model was investigated. Measurements of air velocity were conducted to study the airflow distribution. Computer simulation of the airflow was performed using a widely accepted numerical scheme and the computed results were compared to the experimental measurements. Discussion on the validity of the computed results is presented. Proper design of window positions for optimal ventilation effects is also discussed.

Methods

The Bedroom Model

The single-bed laboratory bedroom model is shown in figure 1 with the x, y, z co-ordinates of direction indicated. The dimensions of the model were 3.00 m in height, 2.40 m wide and 3.00 m in depth. A bed of 1.90 m in length and 0.90 m in width was located as shown. The window opening was 0.60 m wide and 1.20 m in height. The window was centrally placed in the vertical direction, with the wall area 0.90 m above and below. There were four different window positions in the bedroom model, shown as type A to type D. A door opening 0.90 m wide and 2.10 m high was fixed at a position on the opposite side as shown.

The Experiments

Figure 2 shows the schematic diagram of the experimental setup. Uniform air velocity of 0.5 $m \cdot s^{-1}$ at the window opening was achieved by using two honeycomb flow straighteners in the air duct. As in figure 2, a 4.0-metre long air duct and a blower were used to supply a constant air flow to the model bedroom. The low air velocity at the inlet was used to simulate breezy conditions outdoors.

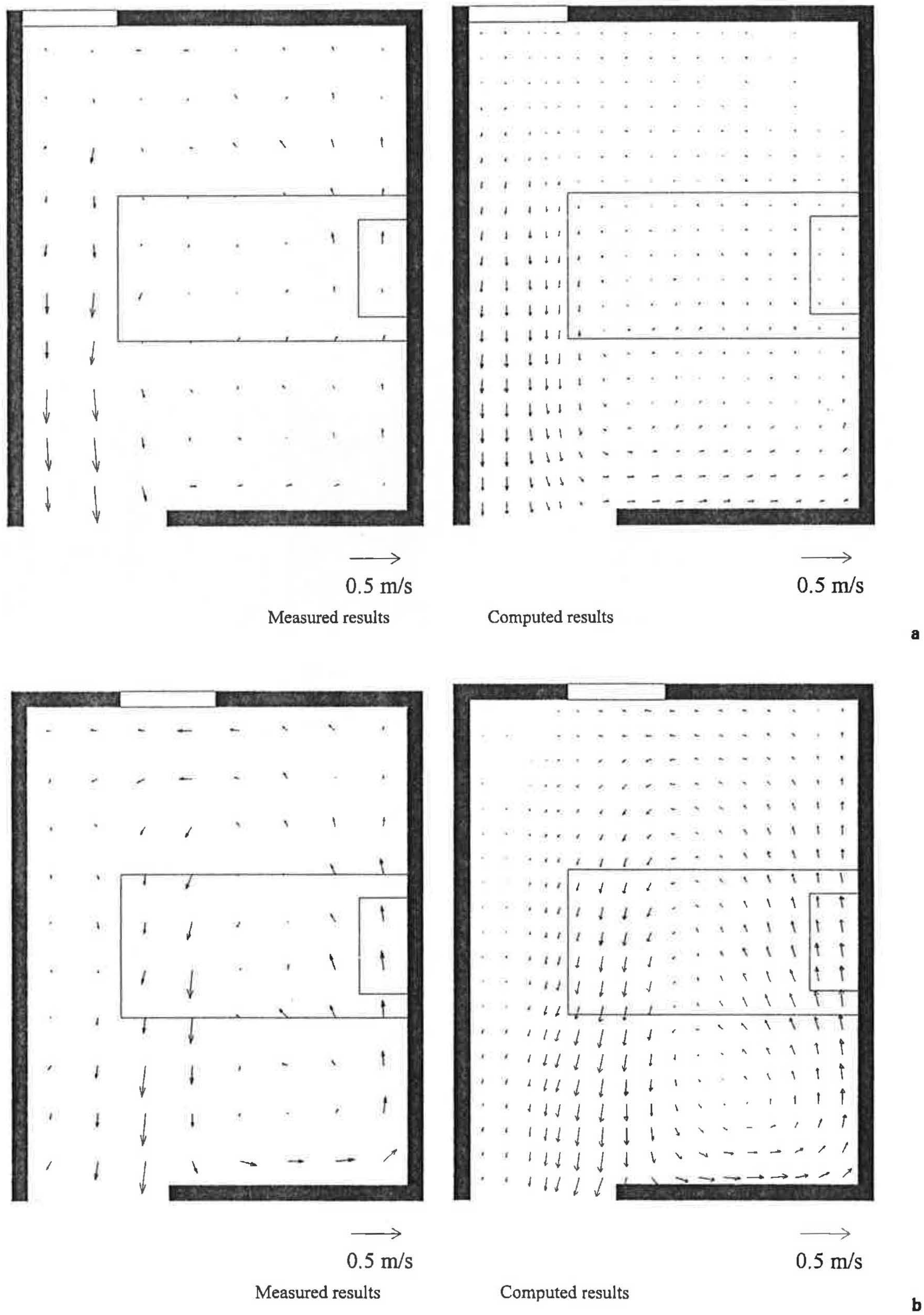
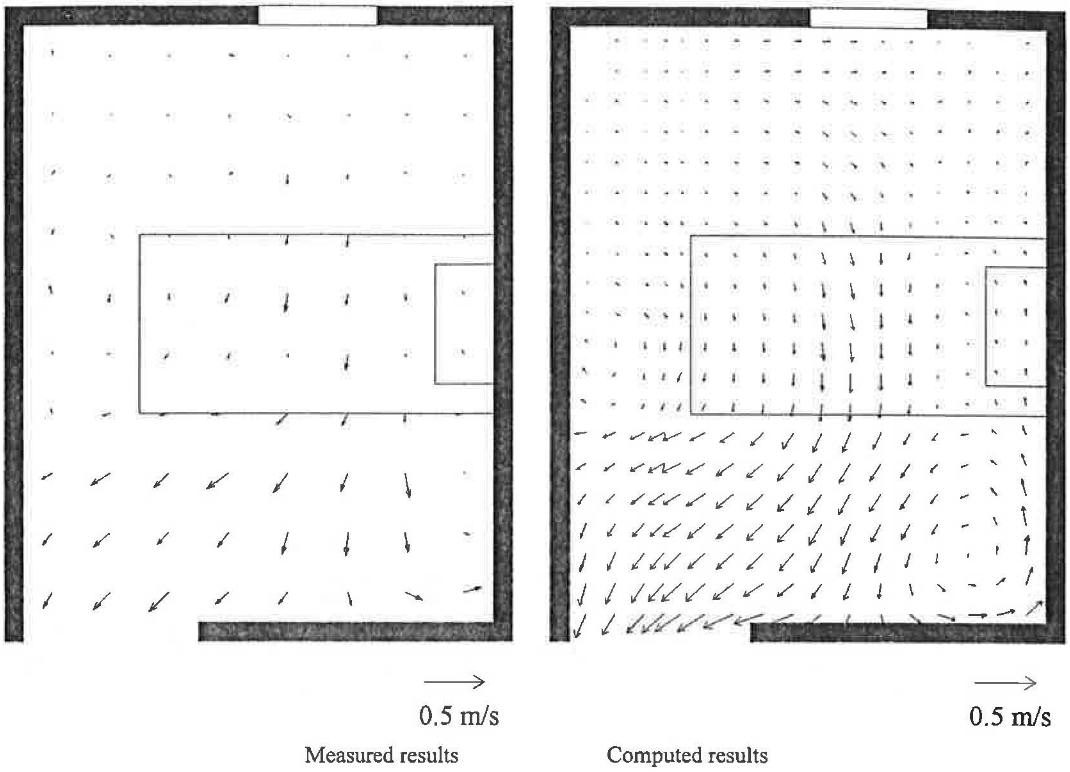


Fig. 3. Airflow distributions for the height of 0.75 m above the floor for the four types of window openings. Measured and computed results for type A (**a**), B (**b**), C (**c**) and D (**d**) window openings.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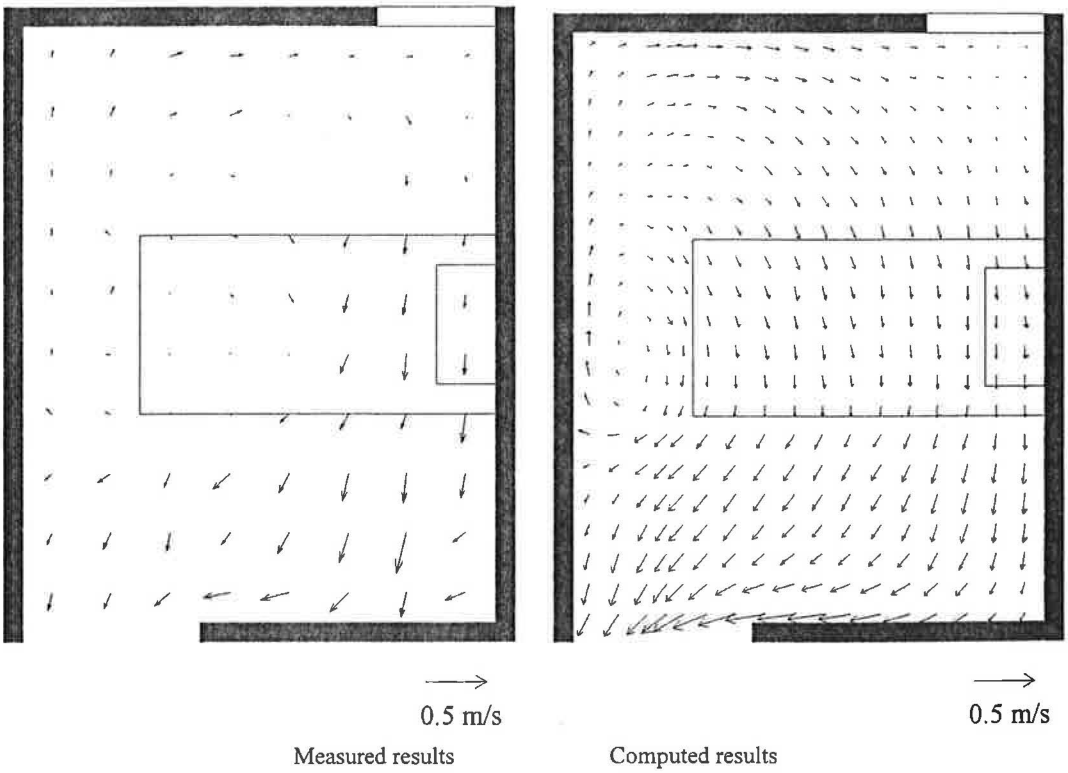
0.5 m/s
Measured results
Computed results

c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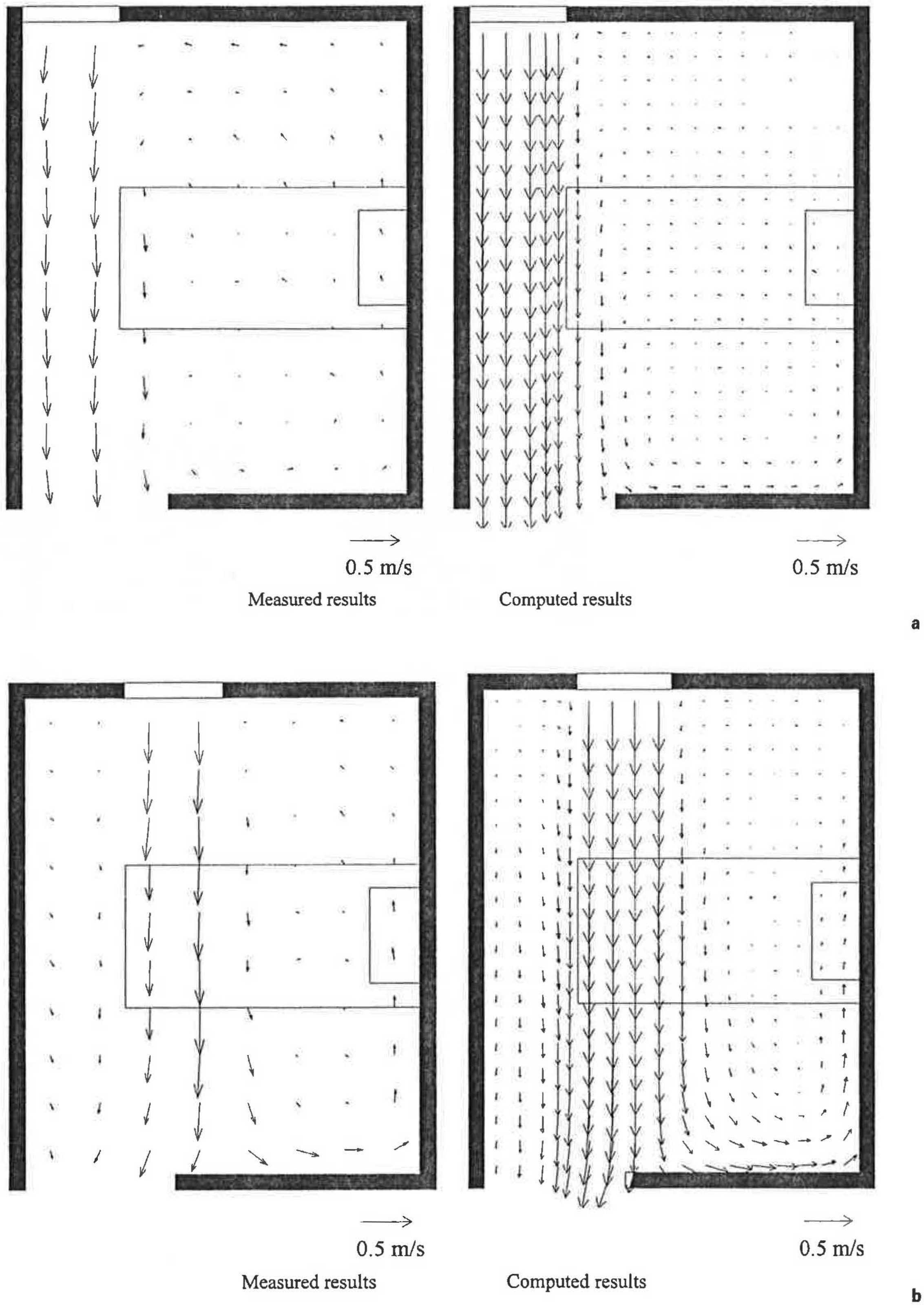
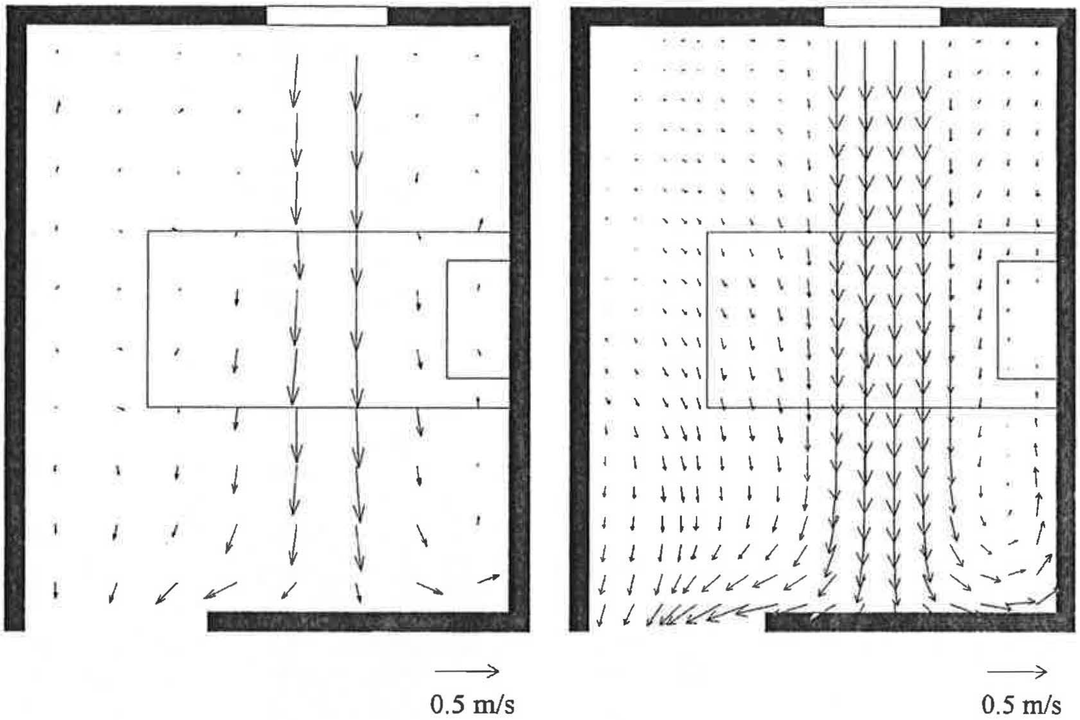
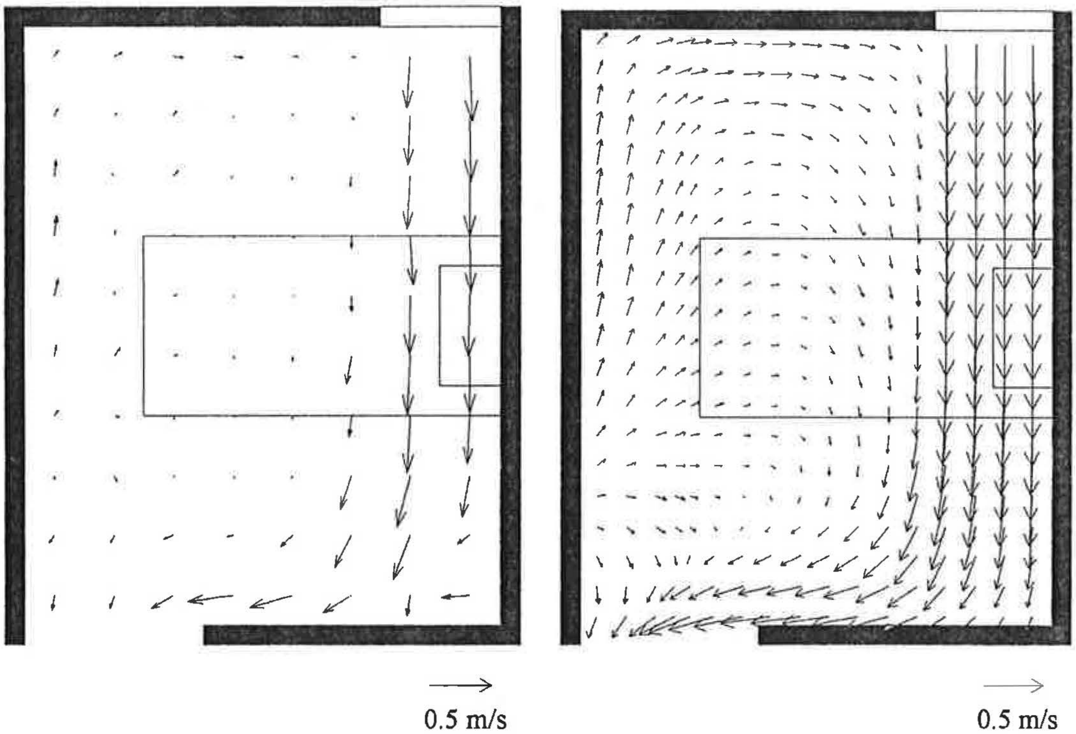


Fig. 4. Airflow distributions for the height of 1.50 m above the floor for the four types of window openings. Measured and computed results for type A (**a**), B (**b**), C (**c**) and D (**d**) window openings.



Measured results　　Computed results

c



Measured results　　Computed results

d

Airflow distributions at two different height levels were measured. The height of 1.50 m above the floor represents the standing breathing zone, and that of 0.75 m above the floor represents the lying breathing zone. For each level, measurements of airflow were taken at 80 equally spaced points. In order to determine the airflow paths, a three-dimensional ultrasonic anemometer (Kaijo Model WA-390, Tokyo, Japan) was used. The ultrasonic anemometer can measure the three velocity components of the air at each point. Therefore, the airflow paths and the flow velocity for each point measured can be obtained. This ultrasonic anemometer was capable of measuring velocity as low as 0.1 $m \cdot s^{-1}$ with an accuracy of 2%. The experiments were designed so that the ultrasonic anemometer was motor driven on tracks to pre-programmed positions, in order to minimize flow obstruction due to the presence of a person working in the room.

Computation of Air Flows

The flow field in the room is induced by air flowing through the window, and isothermal flow distribution is assumed. The governing equations are written as follows: mass conservation: $\rho_{,t} + (\rho U_i)_{,i} = 0$, momentum conservation: $(\rho U_i)_{,t} + (\rho U_j U_i)_J = -P_{,i} - (\rho \overline{u_j u_i})_j$, where U_i, U_j = mean velocity in x_i and x_j directions, respectively, $\overline{u_i u_j}$ = Reynolds stresses for turbulent flow.

When the flow field space is divided into numerous three-dimensional grids, the governing equations of airflow can be converted into difference equations at the grids. Then the difference equations are solved numerically using a computer algorithm. The computer code Phoenics [9] was used in this study. Airflow turbulence was determined by a k-ε two-equation model. The computer code Phoenics is based on a finite volume method that uses the SIMPLE algorithm [10].

The numbers of grids used in the x, y and z directions were 17, 20 and 20, respectively, thus forming a 6,800-grid system. For the purposes of comparison with the experimental measurements, the inlet air velocity was taken to be normal and uniform across the window area. No-slip boundary conditions were applied to the walls. For boundary conditions at the door (outlet), the Neumann conditions (*i.e.* $\partial u/\partial y = \partial v/\partial y = \partial w/\partial y = 0$) were applied. These conditions mean that the three components of the air velocity do not change in the y direction at the door.

Results and Discussion

Results of the experimental measurements and also the computations for the four different types of window openings are presented and compared in figures 3 and 4. Figure 3 shows the airflow distributions at the height of 0.75 m above the floor and figure 4 shows the airflow distributions at the height of 1.50 m above the floor. The figures show that the calculated airflow patterns agree very well with the measured ones. It is especially notable that calculated occurrences of flow circulation match those of the measurements. Also, even a small local circulation was obtained both experimentally and by computation as shown in the right lower corners of figure 3c. This shows that the simulation models used are valid and are proper tools for the study and the design of airflow for bedroom ventilation.

It should be noted that the 0.75-metre height level is below the base of the window, and airflow is largely induced by the flow through the window. Therefore, normal air flows are not seen at the window openings in the results presented in figure 3. For type A and type B, it seems that flow circulation occurs in the other half of the room where the head zone (indicated by a rectangle) of the bed is situated. The measurements and the computation results agree well. The results can be explained by saying that as the incoming flow heads towards the door, the flow circulation for that half of the room is largely induced by the incoming flow.

The above results show that window positions for type A and type B are not ideal for good ventilation at the breathing level when lying. Figure 3c shows that a type C window opening can result in a small circulation zone in the far x-y corner of the bedroom. For both type C and type D, the air circulation occurs in areas that are away from the bed. Therefore, a bed located centrally as shown will be expected to have good ventilation.

The window opening is from 0.9 to 2.1 m from the floor and the 1.5-metre height level is in the direct airflow stream of the incoming flow. Therefore, in figure 4, normal flows are observed at the window openings with a velocity of 0.5 $m \cdot s^{-1}$. Figure 4 shows that stronger air circulation occurs at this height. It also shows that even for the type C window opening, flow circulation at the head zone of the bed is noted in figure 4c. Type A and type B openings show similar flow distributions as for the height of 0.75 m. For these two types, flow circulation occurs at the other half of the room. From the results shown, type C and type D are the better window positions, as they result in better cross-ventilation for the breathing level when lying.

Ventilation at the head zone of the bed is of prime concern. Table 1 shows the air velocities as measured and also as calculated for the head zone of the bed. There are discrepancies between the values of measurement and calculation. However, both the measurement and calculation results show the same trends. It should be noted that for the height of 0.75 m above the floor, type B has a higher airflow velocity than type C, although the window opening is closer to the head zone of the bed. It should be pointed out that air velocity alone is not an indication of ventilation effectiveness. For type B, the head zone is in the circulation zone. Therefore, determining the airflow distribution is of paramount importance for the design of ventilation for a room such as a bedroom with the setting studied.

Table 1. Air velocities measured and calculated for the head zone of the bed

Range	Terms	Mean of air velocity, $m \cdot s^{-1}$			
		type A	type B	type C	type D
0.75 m above the floor	measured	0.11	0.17	0.07	0.18
	predicted	0.02	0.11	0.04	0.16
1.5 m above the floor	measured	0.07	0.09	0.17	0.45
	predicted	0.03	0.03	0.09	0.51

Conclusion

Airflow distribution due to cross-ventilation has been studied for a typical bedroom with a single bed. Three-dimensional airflow distributions in the room were obtained by a computation method and also by using ultrasonic anemometry. Close congruence between the measured and the calculated flow patterns shows that the computation method used can be a good tool in the study of ventilation for such a bedroom setting. Different window positions were tested both experimentally and by computation. The results show that circulation of air in the bedroom can be avoided by proper window positions. Thus, more effective ventilation and a better indoor air quality can be obtained for a cross-ventilated bedroom by design of the window position. Optimal window positions relative to the bed and the door positions are shown and discussed. It is observed that flow circulation occurs at the head zone of the bed for some window positions. It is also shown that knowledge of the air distribution rather than magnitude of velocity alone is more important in determining good ventilation.

Acknowledgments

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