The influence on ventilation efficiency in typical dwelling with floor-based displacement ventilation

Nien-Tsu Chen[a], Yen-Yi Li[a,b], Po-Cheng Chou[b], Che-Ming Chiang[a,*]

[a]*Department of Architecture, College of Engineering, National Cheng Kung University, Taiwan, ROC;* [b]*Department of Interior Design, College of Design, ShuTe University, Taiwan, ROC*

ABSTRACT
The characteristics of the climate in Taiwan are high temperature and humidity. In order to solve these basic problems in dwellings, a meteorological station was established in Fulong (northeastern part of Taiwan) to document the detailed microclimatic information of indoor and ambient environments during 4 years. According to the hydrodynamics and thermal mechanics, the new ventilation strategy was developed with the thermal mass cooling-down system constructed as the porous floor in a full-scale climate chamber. The typical dwelling room is 5.5 m (L) × 2.9 m (W) × 3.05 m (H) with a 0.5 m (H) elevated-floor system. The air intake is located under the elevated floor, and the outlet is the transom window on the other side.

The CFD technology was taken to simulate the ventilation efficiency in the study. The factors we calculated were all set in the same time including pressure drop, velocity, temperature and carbon dioxide (CO_2) concentration. In order to calculate the age of air, the concept of concentration decay method was conducted in the unsteady state solution. Hence, the CO_2 concentration is the tracer gas in the CFD simulation. By validation of full-scaled chamber experiment, the k–ε turbulence model of RANS was adopted in all cases. The opening positions and the opening ratio of the elevated floor were the change factors in this type of displacement ventilation. The most operative conclusion to the designer is the porous ratio of the elevated floor of about 4–6%. The ventilation efficiency achieved is 80%, referred to the pistol flow of 100%. The air exchange efficiency in a typical dwelling with Floor-Based Natural Displacement Ventilation is higher by 10% than the cross-ventilation through transom windows. Besides, the materials of the floor with the cooling and dehumidified effects were studied for the integration solutions of Indoor Air Quality and thermal comfort in Subtropical Regions.

INDEX TERMS
CFD; Ventilation efficiency; Displacement ventilation; Subtropical region solutions

INTRODUCTION
The typical sliding windows and transom windows were most used as general type of openings in Taiwan. However, these types of openings have good air tightness in winter and less opening ratio in summer. The weather in the northern part of Taiwan would always be cold in wintertime, the average temperature is about 10–18°C and the relative humidity is almost above 85%. In good Indoor Air Quality (IAQ) control perspective, the soundproof windows of these types, which maintain good the air tightness, introduce less fresh air exchanges. The indoor air contaminants such as CO_2, formaldehyde, VOCs accumulate continuously and detrimental to human health, especially when sleeping at night time. Therefore, the research aimed at another ventilation strategy of utilizing the principle of floor-based natural displacement ventilation in a dwelling in Taiwan. This new type of dwelling opening design could provide a hybrid ventilation pattern in summer and displacement ventilation in winter. Besides, the thermal

[*] Corresponding author. E-mail: cmchiang@mail.ncku.edu.tw

driving force could be a more perfect air-mixing situation in the room with displacement ventilation. The ultimate goal is to improve the air exchange efficiency in summer and winter, and to keep the indoor environment more comfortable and healthy.

METHODS

The domain of the simulation in CFD solutions contains two primary chambers. One is a chamber set as an outdoor air situation in Taiwan and the other is a model room. The typical model room built in CFD solutions is 5.5 m (L) × 2.9 m (W) × 3.05 m (H) in internal diameter, and the external diameter is 6.1 m (L) × 3.2 m (W) × 3.35 m (H) with a 0.5 m (H) elevated-floor system (Figure 1). Table 1 shows the settings of the five interfaces through which airflows will pass when flowing from outdoor into indoor.

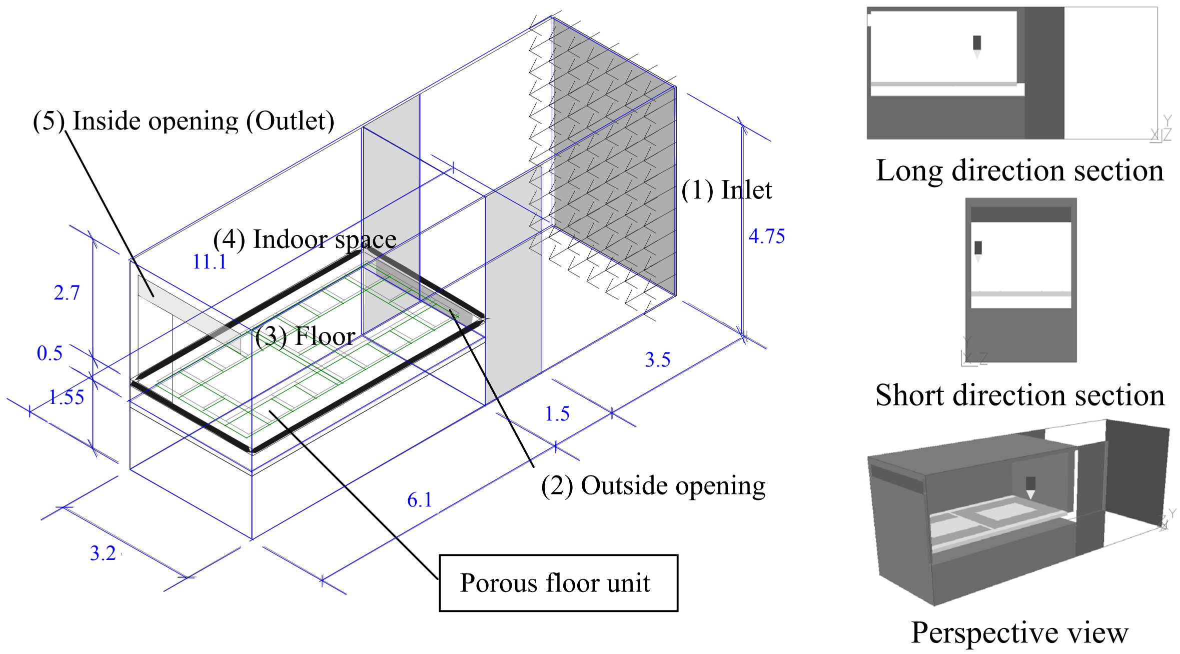


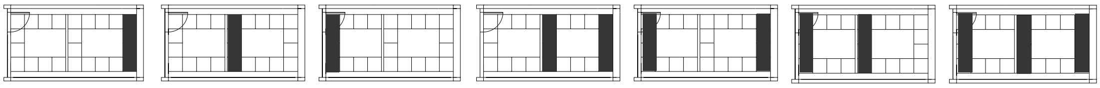
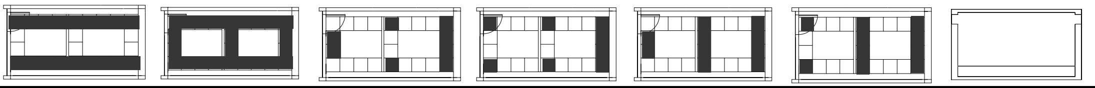
Figure 1 An illustration of the dwelling room.

Table 1 Settings of five interfaces in the domain

Item	Setting
Inlet	Wind velocity = 0.1, 0.3, 0.5, 1, 2 m/s
Outside opening	2.9 m × 0.5 m (under floor)
Floor	Change the positions and amount of porous floor units
Indoor space	No furniture and people
Inside opening (outlet)	2.9 m × 0.5 m (transom window, set negative pressure by the flow fluid simulation of a whole building)

Each porous floor unit was set to be a thin plate and its porosity ratio is 0.215. The porosity ratio is equal to the ratio of porous floor unit in general office or computer rooms in Taiwan. We fixed the porosity ratio of porous floor units, and changed different positions and the amount. Thirteen kinds of different constituent types of the porous floor in the study and one type with transom windows on both sides are shown in Table 2. The positions of the porous floor units were installed by considering the use of space at the same time.

Table 2 All kinds of different constituent types of the porous floor in the study

Number	C01	C02	C03	C11	C12	C13	C21
Amount	4	4	4	8	8	8	12
Figure							
Number	C22	C23	C31	C32	C33	C34	C41
Amount	18	24	8	8	10	10	Two-sided transom windows
Figure							

The porous floor unit; ← The direction of wind.

The characteristics of airflow through the porous floor could be defined by two factors (Miguel, 2000), which should be verified in the setting of CFD boundary conditions. These two factors included the porous ratio (porosity) and the resistance coefficient (*f*) of a thin plate. Therefore, the porous floor plate was set into the wind tunnel to find out the total pressure drop and the change of flow velocities before and after the plate. The pressure and velocity values were measured between the locations, three points in front of the porous plate and six points behind it by different initial wind velocities (Figure 2).

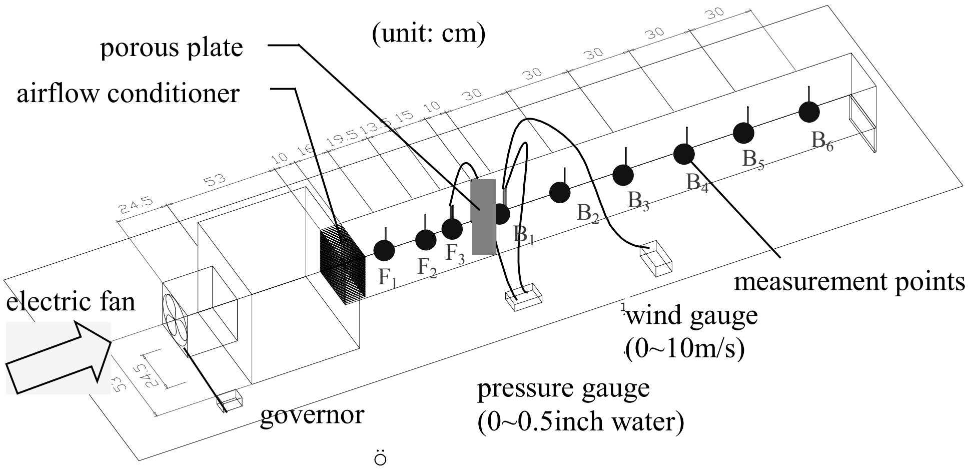


Figure 2 The illustration of the installation in a small wind-tunnel experiment.

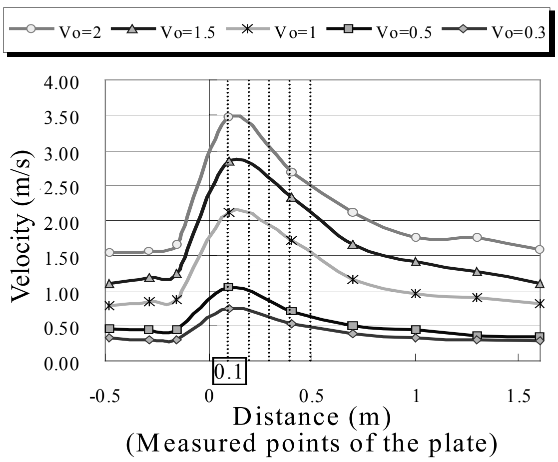


Figure 3 The changes of velocity in a small wind tunnel.

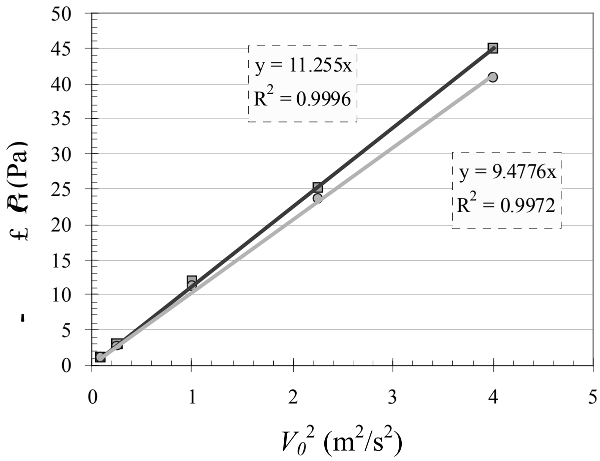


Figure 4 The relation between ΔP and V_0^2.

The results show the airflow velocity would increase suddenly (behind plate within 0.1 m) at first after the airflow crossed the aperture, and decrease gradually (Figure 3). The relationship between the total pressure drop (ΔP) and the square of velocity (V_0) in front of the porous plate is analysed as Figure 4 shows. Obtaining these values and using Eqn (1), the resistance coefficient (f) can be calculated to set the condition of CFD:

$$f = \frac{|\Delta P|}{0.5\rho V^2} \qquad (1)$$

where ΔP (Pa) is a difference of pressures in front and behind a porous material, ρ is air density (1.2 (kg/m^3)) in the condition (1 atm, 20°C) and V is equal V_0 (m/s) is wind velocity in front of a porous material.

Airflow states under several conditions were studied using the CFD technique. As Figure 1 shows, the three-dimensional airflow in the typical model room was analysed both using steady-state analysis and the transit-state analysis technique comparing with the experimental model to compare and find out the real-time ventilation efficiency. The steady-state analysis was helpful to know a general effect of ventilation. The transit-state analysis was done in order to calculate the air exchange efficiency (AEE). Using the Concentration Decay Method we could calculate the mean age of air, the local age of air and AEE. The air change rate, AEE and CO_2 concentration were the evaluated indicators of the ventilation efficiency. The settings of others about CFD solutions were as below. Effect of airflow turbulence was assumed by adopting RANS k–ε model using the finite volume method based on SIMPLE algorithm. The inlet air velocity was assumed to be normal and uniform across the interface cross-section and through the elevated vent floor system. No-slip boundary conditions were applied on the walls. On the outlet side, the Neumann boundary conditions were applied for velocity and pressure boundary conditions. The convergence value is set to 0.01, and each case takes over 48 h to solve for each stage of transit state.

RESULTS

The ventilation rate was based on the location and the opening ratio of the floor-based ventilation system. Therefore, to find out which ratio of the opening is the best choice of floor-based ventilation, concerning about the air change rate and the air exchange efficiency, is the major results of CFD solutions. The relation between the ratio (R) of the openings area to total floor area and air change rate can be drawn as shown in Figure 5. In general, the ratio (R) recommended is over 4% for the natural ventilation achieving effectiveness. However, if the velocity of fresh air can be controlled and supplied constantly like as in machine ventilation systems, the ratio(R) can be designed in accordance with the values that are shown in Table 3. And the difference ratio (R) can assure the indoor environment of maintaining different levels of CO_2 concentration. The ventilation efficiency can represent the airflow path and the distribution. Table 4 shows the two cases that because of different constituent types of floors have different ventilation paths. For example, the case C34 has a better ventilation distribution, and the case C41 (with transom windows both sides) has a short-circulation situation. According to the CFD simulation and the full-scaled chamber test, the AEE value by cross-ventilation through the transom windows on both sides is about 35.9%. However, the AEE values with displacement ventilation are approximately over 44.5% in better cases of the study. It is enough to prove that the ventilation mode with floor-based displacement ventilation is better than with mixing ventilation. Table 5 shows the ventilation efficiency of each case in the study by using different factors to assess.

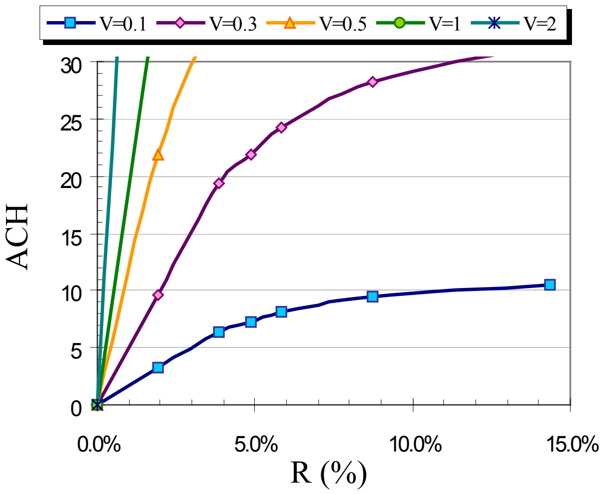


Figure 5 The relation between *R* and ACH.

Table 3 Ratios (*R*) recommended in the study

People	1			2			3			4		
V (m/s)	CO_2 (ppm)			CO_2 (ppm)			CO_2 (ppm)			CO_2 (ppm)		
R (□)	1000	800	600	1000	800	600	1000	800	600	1000	800	600
0.1	1.4	2.2	4.8	3.0	5.1		5.2			13.0		
0.3	0.5	0.8	1.5	1.0	1.5	2.9	1.5	2.3	4.8	2.1	3.0	10.1
0.5	0.2	0.3	0.65	0.45	0.65	1.25	0.65	0.95	1.95	0.85	1.3	2.9
1	0.13	0.2	0.38	0.27	0.4	0.77	0.41	0.6	1.15	0.54	0.8	1.55
2	0.06	0.08	0.16	0.11	0.16	0.31	0.17	0.24	0.47	0.22	0.33	0.62

Table 4 The simulations of the airflow and concentration fields by CFD solutions

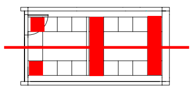
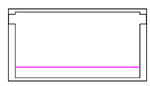
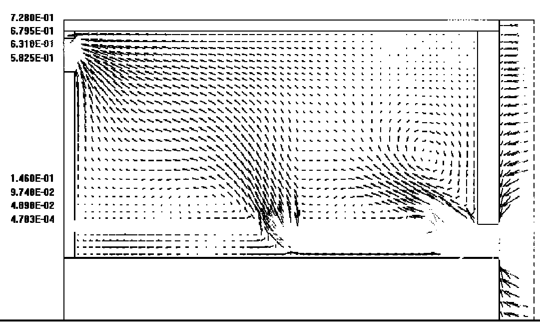
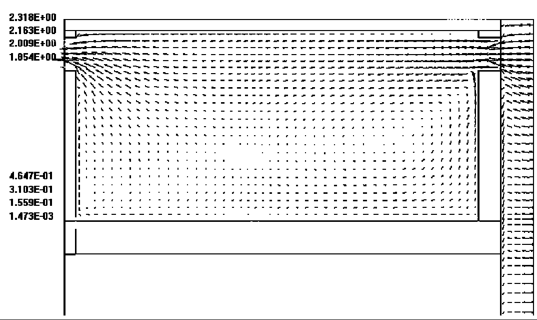
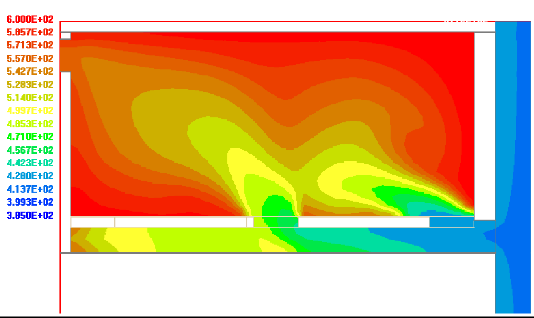
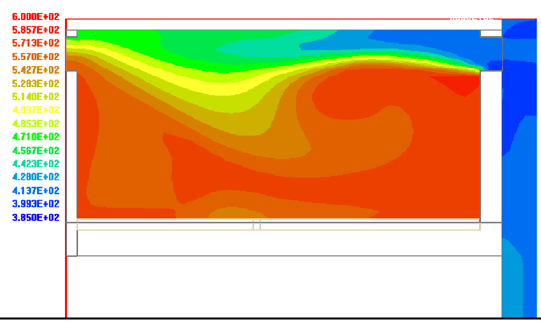
C34		**C41**	
Airflow field		Airflow field	
			
CO_2 concentration field		CO_2 concentration field	
			

Table 5 Ventilation efficiency in all cases in the study

V = 0.1 m/s	C01	C02	C03	C11	C12	C13	C21	C22	C23	C31	C32	C33	C34	C41
ACH (h^{-1})	3.1	3.6	3.2	6.2	6.4	6.3	8.1	9.4	10.5	6.2	6.4	7.3	7.3	10.5
AEE (%)	44.5	43.2	34.3	45.6	43.0	35.1	44.4	35.0	38.7	45.0	43.7	44.6	44.8	35.9
*ΔC (ppm)	115	91	40	148	138	39	136	131	140	142	119	128	137	144

*ΔC = indoor initial concentration minus concentration after 4 min runtime.

DISSCUSSION

This research does not discuss the location of heat buoyancy, such as human heat or computer heat source. Further studies could focus on the increasing effect of buoyancy in wintertime, and the hybrid ventilation effect with this system in summertime. Furthermore, the high humidity level of Taiwan is another important issue that needs to be solved, the material used in floor could be also the thermal and moisture controlling factor. By assessing the effect on ventilation efficiency, the architects could utilize the better mode and calculate the healthy living conditions with this natural displacement ventilation mode.

CONCLUSION AND IMPLICATIONS

The opening positions on the floor should be decided by means of assessing ventilation efficiency and the health factor. There are three situations that should be considered in the design. First, in order to control the indoor airflow well mixed with displacement ventilation, the porosity ratio of the vent-floor unit closed to the intake side should be higher than the outlet side. Second, the height of the intake airway between the floor and the elevated floor should not be less than 20 cm. Third, the opening of the floor should not be arranged continuously and parallel the direction of airflow for reducing wind draft. Synthetically, different amounts of the porous vent floor units and the ratio (R) are the main considered issues, along with the types of porous floor positions. The cases of C01, C11, C31 and C34 are the recommended types and have a better distribution of porous floor units when different ratios of the opening on the floor are needed.

ACKNOWLEDGEMENTS

The authors thank all fellow friends of Archilife Research Center and are supported by a project from National Science Council (NSC91-2211-E-006-102-).

REFERENCES

Chiang, C.M. *et al.* (1999). CFD simulation to predict natural ventilation efficiency in a dwelling bedroom with the central horizontal pivot window. *Indoor Air '99, The 8th International Conference on Indoor Air Quality and Climate*, Vol. 4, pp. 387–390, Edinburgh, UK.

Chiang, C.M., Chou, P.C., Lai, C.M. and Li, Y.Y. (2000). A methodology to access the indoor environment in care centers for senior citizens. *Building and Environment* **36** (4).

Chiang, C.M., Chou, P.C., Li, Y.Y. and Chen, C.C. (2002). The naturally ventilated performances of the transoms installed the porous screens in the conventional kitchen of Taiwan. *Indoor Air 2002*, California, Vol. 2. pp. 884–889.

Li, Y.Y., Wu, P.C., Su, H.J., Chou, P.C. and Chiang, C.M. (2002). Effects of HVAC ventilation efficiency on the concentrations of formaldehyde and total volatile organic compounds in office buildings, *Indoor Air 2002*, California, Vol. 3, pp. 376–381.

Miguel, A.F. (1998). Airflow through porous screens: from theory to practical considerations. *Energy and Buildings* **28**, 63–69.

Miguel, A.F. (2000). Porous materials to control climate behaviour of enclosures: an application to the study of screened greenhouses. *Energy and Buildings* **31**, 195–209.