THE COMBINED WIND AND STACK EFFECTS ON THE INDUCED AIR FLOW VOLUME IN A TWO-STORY BUILDING THROUGH THE INVESTIGATION OF WIND VELOCITY, SOLAR INSOLATION, AND ROOF DESIGN

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ABSTRACT

One sixth of the total energy consumed in Taiwan is for building operation, mainly for summer cooling. The energy consumed for summer cooling can be greatly reduced if natural ventilation can be exerted in Taiwanese urban apartments. To explore the feasibility of applying stack ventilation in urban apartments during warm season of Taipei, this study examines the ventilation volume induced by the combined wind and stack effect in a two story building. The examined parameters are roof design, wind velocity, and solar heat flux. This research is conduced in three-dimensional computational fluid dynamics simulations. It is found that roof type I is able to induce larger ventilation volume when weaker driving forces are considered. Roof type II obtains larger induced air volume when stronger driving forces are considered. In this study, the induced air flow volume ranges from 8 to 14 times of air change per hour. This ventilation volume is much larger than required in a naturally ventilated building when the warm season of Taipei is considered.

INTRODUCTION

More than 95% of the required energy of Taiwan is imported. One third of the total energy is consumed by building business which includes production, transportation, construction, and operation. Half of the energy consumed by building business is for operation, mainly for summer cooling. Taiwan's climate is subtropical. The average temperature for an entire year is 23°C. Summer runs from May to October, and a mild winter from December to February. More than 77% of the total population of Taiwan dwells in urban areas. Around half of the urban buildings are for residence. The major building type of the urban residence is apartment. It is believe that the energy consumed for summer cooling can be greatly reduced if natural ventilation can be considered and emphasized in the design of the Taiwanese urban apartments.

In order to acquire feasible energy conservation strategies of Taiwanese urban apartments, the city of Taipei was chosen as a demonstration to develop for her the design guidelines of natural ventilation for an entire year. Four ventilation seasons are developed. Each season is determined by the amount of the outdoor air required for maintaining indoor thermal comfort and air quality. The four seasons are cold season (December, January, and February), mild season (March, April, and November), warm season (May and October), and hot season (June, July, August, and September). Three major research areas are concerned. They are the analysis of outdoor climate, the design of building envelop, and the design of indoor air flow pattern. Previous research efforts have been made on the design of building envelop and the design of indoor air flow pattern during cold season. The goals of the research works were to acquire high indoor air quality and thermal comfort when outdoor air was used in the cold season [1, 2, 3].

At this stage, the research goal is to explore feasible natural ventilation methods for the warm season of Taipei. In this study , the considered method is stack ventilation. During the warm season of Taipei, the outdoor diurnal temperature is 26°C and the indoor diurnal temperature is 27.5°C in a naturally ventilated building. During daytime, it is appropriate to apply outdoor air for indoor cooling. This study investigates the combined wind and stack effects on the induced outdoor air volume. The stack effect is generated by solar insolation collected on a sloped roof. A two-story building, representing a simplified apartment, is studied. This research is conduced in three-dimensional computational fluid dynamics simulations. An available simulation tool together with the standard k-ε turbulence model are employed in this study.

METHODS

CFD simulations

This study is carried out in 3-D turbulent flow by computational fluid dynamics simulations. PHOENICS [4], a commercially available CFD code, is employed. The applied turbulence model is the standard k-ε model which is widely used among ventilation engineers. The body fitted coordinates system is employed in this study for better geometric representation of the sloped roof. The governing equations are solved in the finite-volume method with a staggered grid system. A hybrid scheme is used for the numerical solution. The algorithm employed is SIMPLEST [4]. To prevent the numerical solution process from oscillating or diverging, three methods are used. They are under-relaxation for the continuity equation, false time-steps for the other dependent variables, and 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 place where a large gradient of variables is present.

two-story building

To explore the feasibility of applying stack ventilation in urban apartments during the warm season of Taipei, this study examines the ventilation volume flow rate induced by the combined wind and stack effect in a two story building (Fig. 1). The examined parameters are roof design [5], wind velocity, and solar heat flux. Two types of roof space (Fig. 2) are studied to find out which one enables the exhaustion of hot air easily. Two wind velocities (0.3 m/s and 3 m/s) are chosen to simulate two conditions: stack effect as the dominant driving force and both of stack and wind as the driving forces. Three kinds of solar heat flux are applied to the sloped roof surface. They are chosen to simulate the climate of Taiwan with low solar insolation (200 W/m^2), average solar insolation (500 W/m^2), and very high solar insolation (900 W/m^2). There are 12 cases to be investigated (Table 1). The dimensions for the simulations are shown in Table 2. The initial temperature for the entire domain is 24°C. All simulations are conducted in 32 x 34 x 52 cells.

RESULTS

The following sections present and explain how solar heat flux, wind velocity, and roof type affect the amount of the induced ventilation volume.

solar heat flux

From Table 3, one can find that the induced air flow volume increases with an increasing solar heat flux when a certain wind velocity and roof type are considered. This phenomenon exists in almost all the groups examined except for the group with roof type I by wind velocity of 3 m/s. In this group, the highest induced air volume is obtained by solar heat flux of 200W/m^2 (case s2-v3-I), followed by 900W/m^2 (case s9-v3-I) and 500W/m^2 (case s5-v3-I). One can observe in Table 3 that case s2-v3-I achieves an exceptional high induced air volume. The reason for the high induced volume has not yet been identified.

wind velocity

One can observe in Table 3 that the high wind velocity may not always induce more air volume than the low wind velocity. When the lowest solar heat flux (200W/m^2) is considered, the high wind velocity achieves larger induced air volume than the low wind velocity. When the solar heat flux increases, only by roof type II can the high wind velocity induce larger outdoor air volume than the low wind velocity. It is found that the high wind velocity induces less air volume than the low wind velocity when the solar heat flux is higher than 200W/m^2 and the roof type I is considered. The roof type may account for the reason why the high wind velocity cannot induce larger air volume when a higher solar heat flux is considered. The influences of the two roof types on the induced air volume are elaborated in the next section.

roof type

From Table 3, one can observe that roof type I achieves larger induced air volume than roof type II when the lowest solar heat flux is considered. When the solar heat flux increases, roof type I still obtains higher induced air volume than roof type II only when the low wind velocity is considered. When the high wind velocity and a higher solar heat flux are applied, roof type I obtains less induced air volume than roof type II.

One can conclude from Table 3 that the roof type I is able to induce larger air volume than the roof type II when weaker driving forces are considered. Roof type II obtains larger induced air volume when stronger driving forces are considered. The considered driving forces are wind pressure and stack pressure. The reason for roof type I to achieve larger induced air volume at weaker driving forces is that this roof design provides enough space under the roof for the effective removal of hot air. This phenomenon can be observed in Fig. 3. Compared with Fig. 3(b), Fig. 3(a) has more room for the induced air stream from the building shaft to flow through the inclined heated roof surface. The movement of the hot air in the roof space is hindered by more friction when the roof type II is employed. This is why roof type I can induce larger air volume. The reduction in the induced air volume caused by the hindrance from the design of the roof type II may become prominent when weaker driving forces are applied.

The cause for roof type II to obtain larger induced air volume at stronger driving forces is that this roof design makes the removal of hot air directly by avoiding mixture and circulation in the roof space. Comparing with Fig. 3(a), one can observe that a large circulation area near the bottom of the roof in Fig. 4(a). This circulation is generated by the high momentum produced from a large induced ventilation volume induced by large driving forces. The circulation promotes mixture between the heated air along the inclined roof surface and the cold induced air from building shaft. It is believed that the mixture in the roof space may diminish the exhaustion of the hot air from the building chimney. The diminution is caused by the reduced driving forces. The reduced driving forces are caused by the dropping temperature of the hot air along the inclined surface when the hot air is largely mixed with the induced cold air. Therefore, by avoiding such mixture, the roof type II is able to induce more ventilation volume by removing the hot air directly and effectively (Fig. 4(b)).

DISCUSSION

From Table 3, one can find that the induced air flow volume denoted by the number of air change per hour (ach) ranges from 8 to 14 times. It is believed that the induced air volume for ventilation is much larger than required in a naturally ventilated building when the warm season of Taipei is considered. For further investigation of the stack ventilation design, the occupant control of the induced air volume and the indoor distribution of the induced air stream have to be examined. In addition, the influences of different window locations corresponding to wind direction on the induced air volume should be investigated when urban apartments are concerned.

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Table 1 Simulation cases

type	s2				s5				s9			
	s2-v0.3		s2-v3		s5-v0.3		s5-v3		s9-v0.3		s9-v3	
case	I	II	I	II	I	II	I	II	I	II	I	II
solar heat flux (W/m^2)	200	200	200	200	500	500	500	500	900	900	900	900
wind velocity (m/s)	0.3	0.3	3.0	3.0	0.3	0.3	3.0	3.0	0.3	0.3	3.0	3.0
roof type in Fig. 2	I	II	I	II	I	II	I	II	I	II	I	II

Table 2 Dimensions and locations for simulations

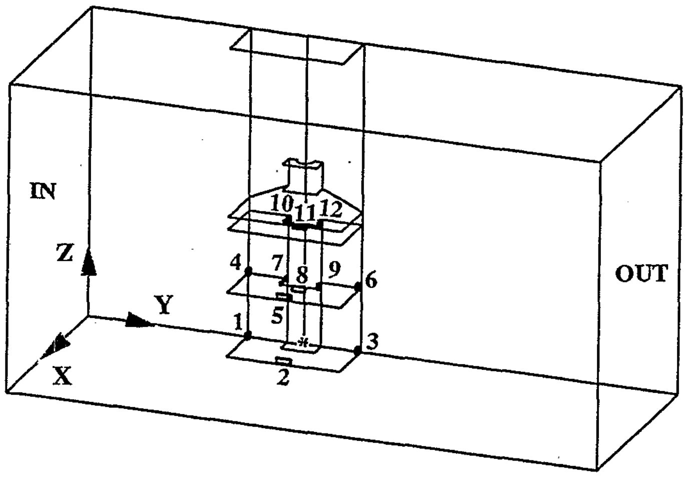
DIMENSION (m)	X	Y	Z	LOCATION[2] (m)	X	Y	Z
simulation domain	9.50	26.00	16.00	two story building	0.00	7.00	0.00
two story building	2.50	5.00	10.20	window 1	0.00	7.00	0.00
first & second floor	2.50	5.00	3.50	window 2	2.50	9.20	0.00
windows 1 & 4; 7 & 10	0.30	0.00	0.30	window 3	0.00	12.00	0.00
windows 2 & 5; 8 & 11	0.00	0.60	0.30	window 4	0.00	7.00	3.50
windows 3 & 6; 9 & 12	0.30	0.00	0.30	window 5	2.50	9.20	3.50
outlet on chimney top	0.35	0.70	0.00	window 6	0.00	12.00	3.50
building core/chimney	0.75	1.50	10.20	window 7	0.00	7.00	3.20
chimney above roof	0.75	1.50	1.50	window 8	2.50	9.20	3.20
low gap, a in Fig. 2	0.00	0.00	0.20	window 9	0.00	12.00	3.20
side gap, b in Fig. 2	0.00	0.30	0.00	window 10	0.00	7.00	6.70
roof gap, c in Fig. 2	0.00	0.00	0.21	window 11	2.50	9.20	6.70
				window 12	0.00	12.00	6.70

[2]measured from the origin of the coordinates to the upper left corner of each object, viewed from +X

Table 3 Induced air flow volumes

type	s2				s5				s9			
	s2-v0.3		s2-v3		s5-v0.3		s5-v3		s9-v0.3		s9-v3	
case	I	II	I	II	I	II	I	II	I	II	I	II
ach[1]	8.47	8.12	13.32	10.13	11.26	10.93	10.25	11.49	13.50	13.23	12.54	13.75
out (m3/s)[2]	0.187	0.180	0.295	0.224	0.249	0.242	0.227	0.253	0.299	0.293	0.277	0.304
window 1[3]	0.038	0.033	0.258	0.256	0.040	0.038	0.261	0.261	0.045	0.044	0.260	0.260
window 2[3]	0.032	0.028	-0.208	-0.209	0.048	0.042	-0.218	-0.198	0.061	0.058	-0.195	-0.191
window 3[3]	0.026	0.026	0.101	0.083	0.033	0.031	0.068	0.084	0.039	0.038	0.092	0.095
window 4[3]	0.034	0.034	0.253	0.256	0.041	0.040	0.254	0.265	0.047	0.047	0.261	0.260
window 5[3]	0.033	0.032	-0.148	-0.195	0.051	0.048	-0.210	-0.198	0.065	0.064	-0.180	-0.170
window 6[3]	0.027	0.026	0.040	0.038	0.034	0.033	0.066	0.031	0.040	0.040	0.043	0.053

[1]number of air change per hour, [2]volume flow rate at outlet; [3]volume flow rate at window location (Fig. 1)



*origin of body fitted coordinates system

Fig. 1 Simulation domain

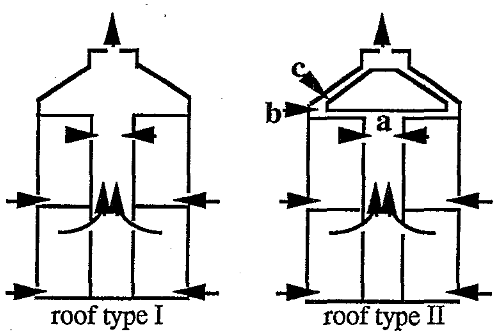


Fig. 2 Two roof types

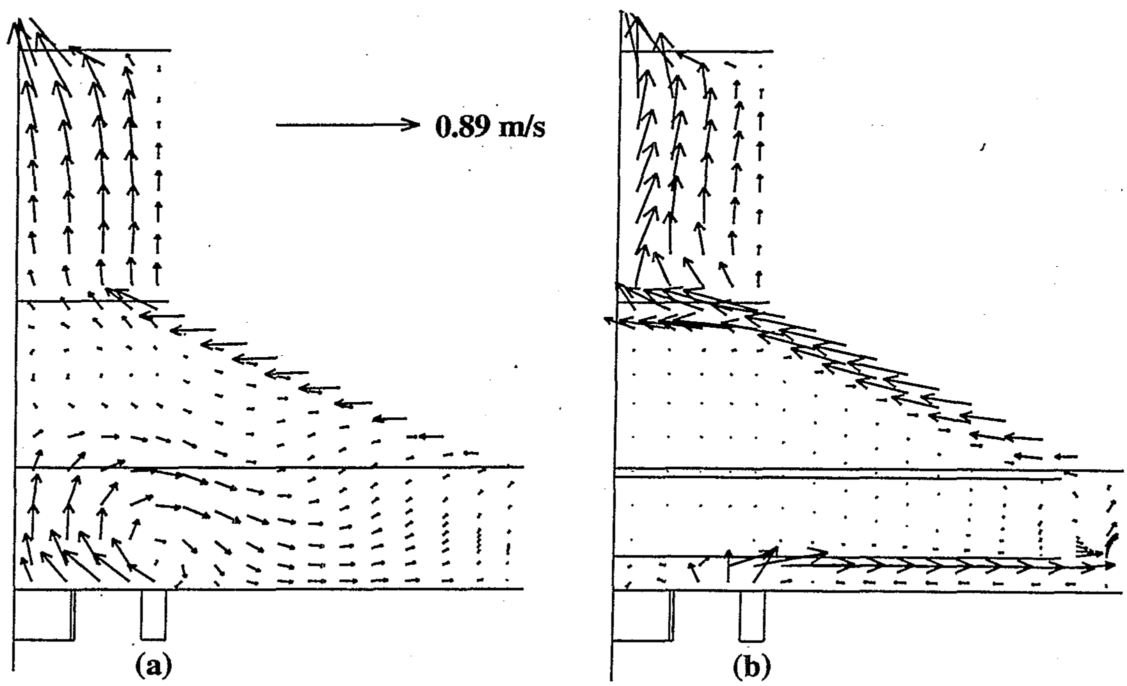


Fig. 3 Flow field in the roof at x = 2.5 m, y = 0.0 m, z = 7.0 - 10.2 m for cases (a) s5-v0.3-I and (b) s5-v0.3-II

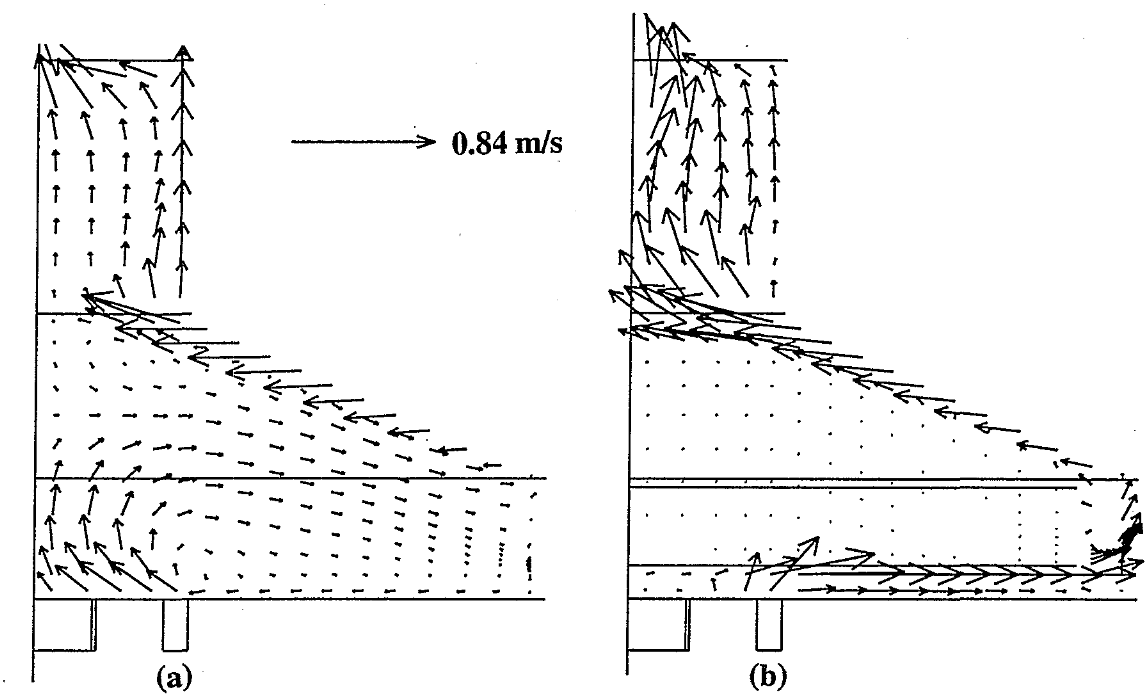


Fig. 4 Flow field in the roof at x = 2.5 m, y = 0.0 m, z = 7.0 - 10.2 m for cases (a) s5-v3-I and (b) s5-v3-II