WIND TUNNEL EXPERIMENT ON THE EFFECT OF WIND ON SMOKE EXHAUST SYSTEMS FOR A HIGH RISE BUILDING

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ABSTRACT

Natural or mechanical smoke exhaust systems are supported to install in tall buildings for removing hot smoke from fire in Taiwan's building code. Normally, the mechanical smoke exhaust volumes are designed according to floor area or given an assigned value of 120 m^3/min. An opening area of 2 m^2 or 3 m^2 is commonly used for natural smoke exhaust vent in Taiwan's building code. However, the wind effects on tall buildings are not included in Taiwan's building code or fire safety regulations. The smoke exhaust systems are strongly influenced by wind effects, especially, for tall buildings. Therefore, an experimental study using a wind tunnel was conducted to investigate the fire pressure and wind induced pressure around tall buildings. Improvements of the design of the smoke exhaust systems of tall buildings were submitted according to the test results. A height-to-wide ratio 4:1 model building was adapted to measure wind pressure in a wind tunnel with a 4 m x 2.6 m cross section area. Three important smoke exhaust system design parameters, building height, smoke temperature and wind angles are adopted to analyze the wind tunnel test results. The study will present useful and practical design limitations of natural/mechanical smoke exhaust system for different building heights.

KEYWORDS: Smoke exhaust system, Smoke vent, Tall building, Wind tunnel

INTRODUCTION

The design of smoke exhaust systems for tall buildings is simple in concept but complex in practice because of the many uncertainties which influence the values that need to be decided for the design parameters involved. Smoke flow in buildings is due to small differences in air pressure caused by the presences of the fire, the larger pressure differences caused by mechanical smoke exhaust fans, and those caused by the natural wind pressure. It is important for smoke exhaust systems to maintain a pressure difference with the environment within limits, so that the forces may drive hot smoke to act freely or negate it. The limits of smoke momentum need careful definition; failure of the system can be obtained as beyond these limits, although failure may not be complete in some circumstances. Butcher et al.[1] measured the maximum pressure difference caused by enclosure fire at the top of a door is almost 5 Pa. The pressure on the fire side of a door will be influenced by the leakage of the compartments surrounding the fire space. However, most buildings are sufficiently leaky not to generate a greater pressure for the fire. For a tall building, the smoke exhausted through a vent or staircase may have a strong buoyant force caused by the fire that will exhaust hot smoke outside naturally.

The atrium may be treated as a tall building in some aspects. In a tall atrium fire, the mass entrainment rate into the rising plume increased rapidly with the height of rise of the plume, a higher smoke layer height would result in a higher smoke exhaust rate. Some practical limitations to the use of vent through the atrium are submitted by Morgan[2]. There is maximum mass flow rate of 150 to 200 kg/s and/or minimum smoke layer temperature of 20^{o}C above the vent. These limitations can be applicable to either a static ventilation system or a mechanical ventilation system. Based on the estimation of the mass entrainment rate of the balcony spill plumes, they suggested that one or another limit is usually reached when the height of rise above the fire room opening exceeds 8 to 12 m. When the tall building or atrium has a certain height the wind pressure may have positive or negative effects on the smoke exhaust systems.

The wind pressure was recognized as an important design parameter for a successful natural/mechanical smoke exhaust system for a tall building. Wind acting on the surface of a simple rectangular building will generate a positive pressure on the side normal to the flow and negative pressures on the other three sides and the top surface[3]. For example, an incident wind speed of 18 m/s will give a nominal stagnation pressure of 200 Pa. The actual pressure will depend on the distribution of pressure coefficients over the surfaces of a tall building. The variability of the effects of wind pressure on fire disasters can be found on some reports[4, 5]. In some cases, staircases may be full of hot smoke and not available for occupant's evacuation when the wind pressure is greater than the hot smoke buoyancy force in the staircase. It seems that the principal effect of wind on the building is to generate horizontal movement of air. The pressure due to wind effect is much larger than the pressure difference due to the volume output of a fire and the buoyant force between smoke and ambient air[6]. Therefore, the wind effects shall be considered in designing the smoke exhaust system for tall buildings.

WIND PRESSURE ON BUILDING

The speed of the wind passing over a point on the ground will vary with height because of the surface drag provided by the surface of the ground downwind of the point. The variation with height is expressed as a power law whose exponent is selected with respect to the nature of the terrain[7]. The equation may be expressed as:

$$\frac{V_w}{V_m} = kz^a \qquad [1]$$

where V_w is the wind speed (m/s), V_m is the meteorological wind speed at 10 m (m/s), κ is the coefficient relating to wind speed to height, z is the building height (m), and *a* is the exponent relating wind speed to height.

For precision predicated the wind speed at local area, actual wind speed of Taiwan city from weather bureau are used to obtain the κ and *a* values from regression. Once the profile of the wind at a location has been established, this can be modeled in wind tunnel and then the flow directions over, and pressures developed on, the surfaces of scale models can be observed and measured.

EXPERIMENTAL FACILITIES

Using wind tunnels to measure wind pressure on model buildings and mass-transport were investigated since 1950. Wind tunnel studies at the National Physical Laboratory and at Colorado State University revealed that physical modeling of wind effects requires a properly simulated boundary-layer flow. This finding was reinforced by comparison of mean pressure measurements at the Wind Laboratory, Technical University of Denmark, on a 1:20 scale model in a wind tunnel with field measurements on the full-scale building[8]. A closed-circuit low-speed wind tunnel was used to measure the wind pressure coefficient on a model building in this examination.

Wind Tunnel Facility

The tests were conducted in a boundary-layer return type wind tunnel whose cross-section is 3 m high x 4 m wide, as shown in Fig. 1. The airflow velocity is adjustable in a range 0-25 m/s. Wind is simulated using calibrated roughness on the tunnel floor for scales ranging from 1/50 to 1/500. An axial fan with a diameter of 1.5 m and 16 adjustable blades is driven by a 150 kW electric motor mounted in the fan nacelle. A maximum free stream wind speed of 13 m/s can be obtained at the entrance of the test section. A rotation pan is assembled on the floor of wind tunnel to simulate different wind direction of the object. A 4:1 aspect ratio acrylic resin building model was placed on the rotation pan. At first, the building scale model was set to perpendicular to the wind direction and the pan was rotated at angles of 0, 30, 60, 90, 120, and 150 respectively. The wind speed was measured with combined vane/temperature probes of 16 mm diameter. These probes are appropriate to measure wind speeds up to 60 m/s, yet the ideal wind speed ranges from 4 to 40 m/s. All probes were calibrated and given, considering their accuracy which is 0.5 m/s, the same value. The Renolds number is approximated as 3×10^5 constantly during the test processing.

No.	No.
1. Screen	4. Adjustable ceiling
2. Honeycomb	5. Screen
3. Rotatable pan	6. Fan

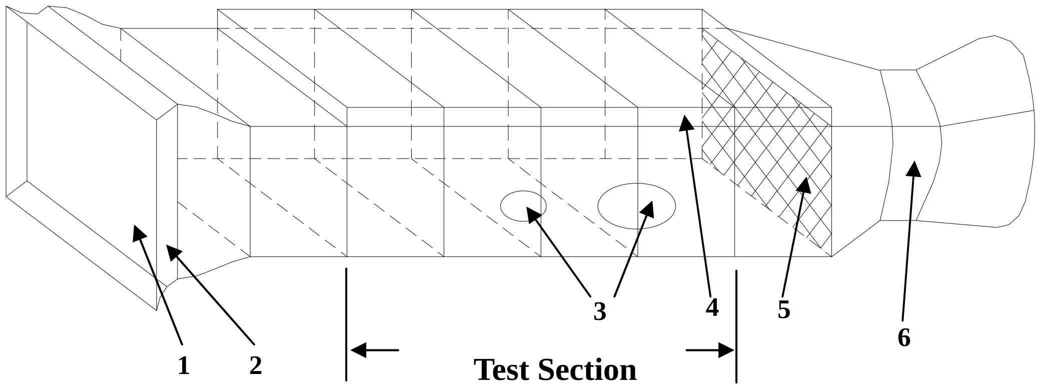


FIGURE 1. Schematic of the experimental wind tunnel

Instrumentation

Experimental results of the wind tunnel tests are the pressure coefficient on the model building at different heights and wind angles. The wind pressure coefficients were measured by an electric pressure scanner which may scan 200 samples per channel per second. A total of eight levels were designed for recording the wind pressure coefficient at six points of each level. The dimensions of the building model are 1.80 m x 0.46 m x 0.375 m and have 15 levels. Each level drills three holes and the diameter of each hole is 1.02 mm. A total of 12 pressure holes are present at each level. During the experiments, readings from the electronic pressure scanner were continuously sampled at 100 Hz for at least 3 minutes. Also, a constant temperature anemometer was coupled with a hot wire probe to measure the wind speed. Therefore, the performance of the smoke exhaust system due to wind pressure coefficient at different building heights can be easily evaluated.

RESULTS AND DISCUSSION

The complete wind pressure coefficients were recorded during the tests. Table 1 lists the values for no. 1 to no. 3 at lowest level and no. 22 to no. 24 at highest level around the model building. The higher level of model building the greater positive/negative pressures may be obtained around the model building. The greatest wind pressure was found at the windward surface where the wind angle is zero. Negative pressures were measured at both left and right hand sides of model building. The largest negative pressure was recorded at the top level of the normal surface. The actual pressure will depend on the distribution of pressure coefficients over the windward side reduce laterally and above the point of maximum stagnation pressure but will reduce less below this point because of the downward flow of air.

TABLE 1. Wind tunnel test pressure coefficient at zero degree wind angle

	Number on model building surface					
	No.1	No.2	No.3	No.22	No.23	No.24
Normal surface	1.0108	1.1462	1.0215	0.6745	0.6922	0.6518
Back surface	-0.4758	-0.4596	-0.4764	-0.6201	-0.6245	-0.6191
Left surface	-0.5230	-0.5648	-0.6484	-0.5919	-0.5794	-0.6043
Right surface	-0.6408	-0.5642	-0.5243	-0.6107	-0.6019	-0.5904

Smoke Exhaust System for Residential Area

The existing Taiwan's building code has two categories about smoke exhaust system for tall buildings. One is for residential areas, and another is for elevator lobby areas. Either natural or mechanical smoke exhaust systems are available for tall buildings in Taiwan. In building code asked the mechanical smoke exhaust volumes must be 120 m^3/min and/or larger than per meter square floor area for one cube meter smoke exhaust volume. Therefore we can examine the performance of smoke exhaust system using this critical value. Neglecting the contraction coefficient of the opening the pressure difference may be calculated as the following equation;

$$\Delta P = \frac{m^2}{2\rho A^2} \qquad [2]$$

where m is the smoke exhaust mass (kg/s), ρis the smoke density (kg/m^3), and A is the smoke vent size (m^2).

When the area of smoke exhaust vent was 0.64 m^2 and 0.48 m^2 the pressure difference will be 2.4 Pa and 10.41 Pa, respectively. Comparing the values with the pressure difference by wind tunnel, a useful evaluated criterion may be obtained from Fig. 2. Smaller smoke exhaust vent offers greater smoke exhausted momentum, thus, mechanical smoke exhaust systems can work efficiently in higher building heights. However, the mechanical smoke exhaust vents are still strongly recommended to install on the roof because the roof has the largest negative pressure difference. The smoke exhaust effective building height moved from 30 m to 130 m when the area of smoke exhaust vent reduced from 0.64 m^2 to 0.48 m^2.

Vents are frequently used for natural smoke exhaust system in residential areas for tall buildings. In Taiwan's building code the natural vent must be installed within 80 cm beneath the ceiling. Inside the fire compartment the relationship between hot smoke temperature and pressure difference was reported by Tamura[9]. Following the smoke temperature a natural height may be obtained from equation [3].

$$Z_n = \frac{P_i - P_o}{(\rho_i - \rho_o)g} \qquad [3]$$

where Z_n is the natural height of smoke vent/window, P is the pressure, ρis the density (kg/m^3), i represents the fire room, and o represents outdoor.

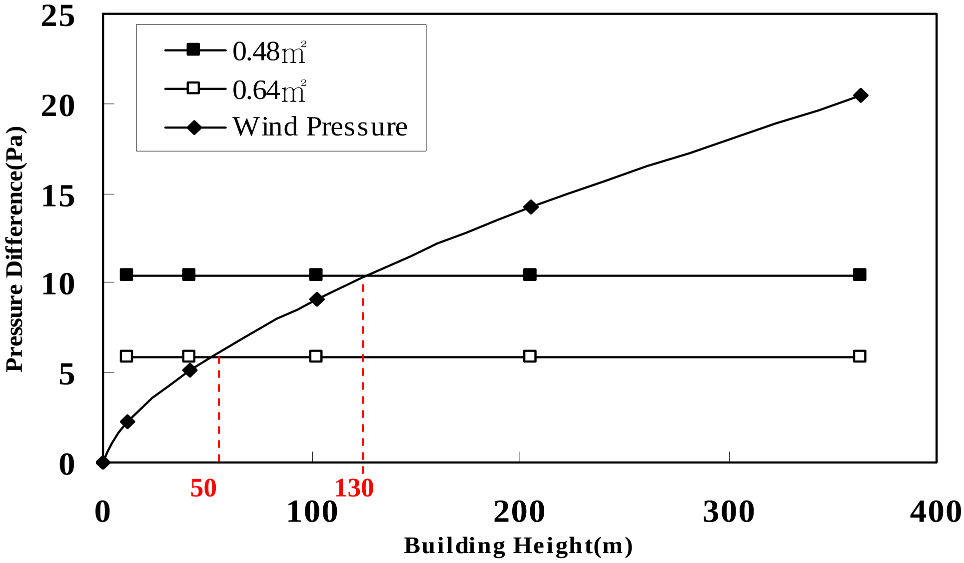


FIGURE 2. Variation of pressure difference with building height at normal wind direction (zero wind angle) for residential area

When Z_n is less than the height of bottom of vent from floor (H_b), it means that the pressure inside fire room is greater than outside. Therefore the hot smoke may flow through the vent automatically. Conversely, for the Z_n larger than the height of top of vent from floor (H_t), the hot smoke may not able to flow through the vent due to the wind pressure. A schematic diagram was shown on Fig. 3 for a size of 0.8 m x 0.6 m vent installed 80 cm beneath the ceiling. Fig. 4 demonstrates the relationship between hot smoke temperature and natural height of vent with different building heights. It is clear when the smoke temperature is greater than 300^o C, hot smoke may flow through vents to outside at 100 m building height because the buoyancy of hot smoke provided larger pressure than the buoyancy of wind. The smoke flowed outside naturally only at less than 60 m the building height at smoke temperature less than 200^o C. At the beginning of fire, the hot smoke was not able to flow outside at the building height greater than 60 m due to wind pressure. Therefore, the fire suppression equipments, such as sprinklers were required for tall buildings to control the fire at the beginning of burning. In the regulations, the vent size must be greater than 2% of floor area of the smoke compartment. It is appropriate for most 100 m height of buildings to use natural smoke systems to exhaust hot smoke after the smoke temperature is higher than 300^o C.

Smoke Exhaust System for Elevator Lobby Area

Another important area applied for smoke exhaust system is elevator lobby/stairwell area which provides a safety evacuative route for occupants. In Taiwan's building code, 4 m^3/sec smoke exhaust volume is required for mechanical smoke exhaust system at lobby area. The comparison results are illustrated in Fig. 5. For size of 0.8 m^2 and 1.0 m^2 vents the critical building height are 200 m and 110 m respectively for mechanical smoke exhaust system working effectively under the zero degree wind direction. The higher building height reduced the smoke exhaust volume through smoke exhaust vent. Therefore, installing the smoke exhaust vent on the roof is the most effective way for mechanical smoke exhaust systems for tall buildings because of the negative pressure difference on roof.

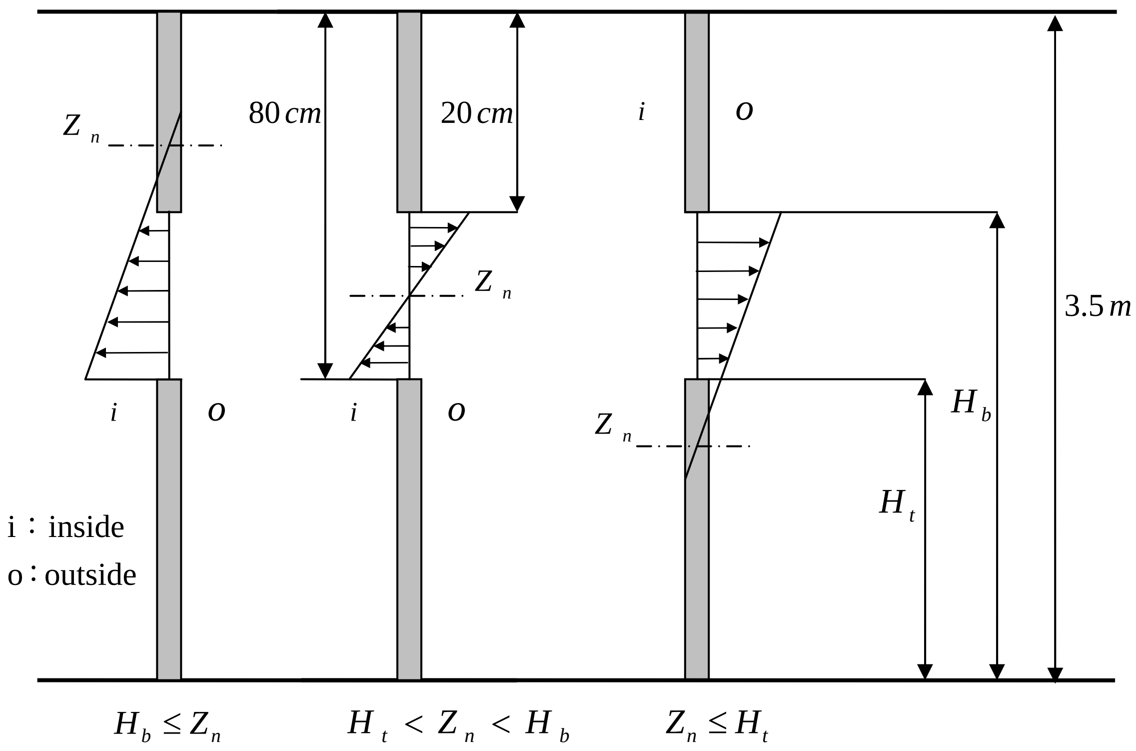


FIGURE 3. The flow direction at different natural heights for a natural vent/window

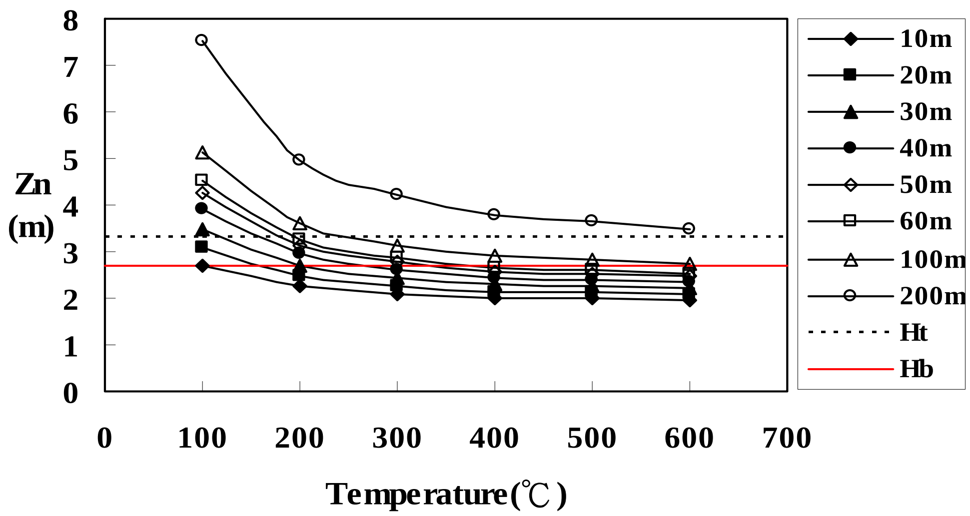


FIGURE 4. Variation of natural height with smoke temperature for different building heights

In Taiwan's building code, the natural smoke exhaust vent/window shall be located at half the height of floor with minimum size of 2 m^2 of elevator lobby area. In practice, the location of natural vent influences the smoke exhaust performance greatly. Thus, two different locations of natural smoke vent/window are investigated in this study. As shown in Figs. 6 (a) and (b), 75 and 20 cm are used to compare the smoke exhaust performance on the same wind effect respectively. At the same smoke temperature the effective building height for smoke exhaust system may rise from 30 m to 60 m when the vent location move up from 75 cm to 20 cm down below the ceiling. The location of smoke exhaust vent is strongly recommended to be installed near the ceiling as possible for highest natural smoke exhaust performance.

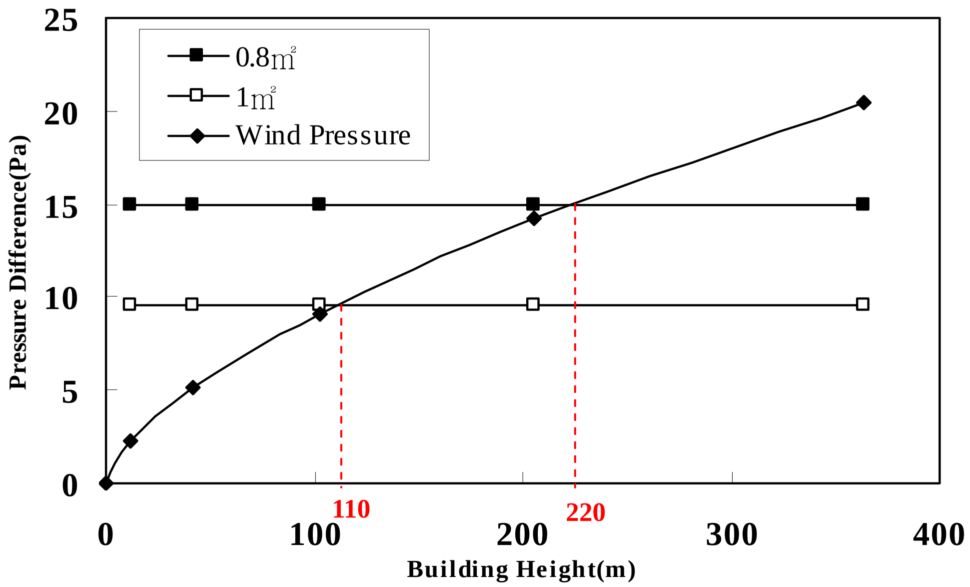
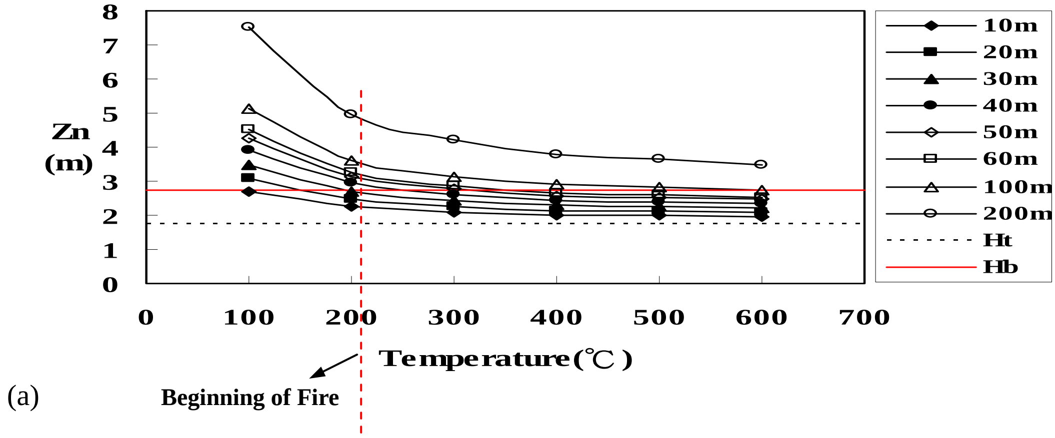


FIGURE 5. Variation of pressure difference with building height at normal wind direction (zero wind angle) for elevator lobby area



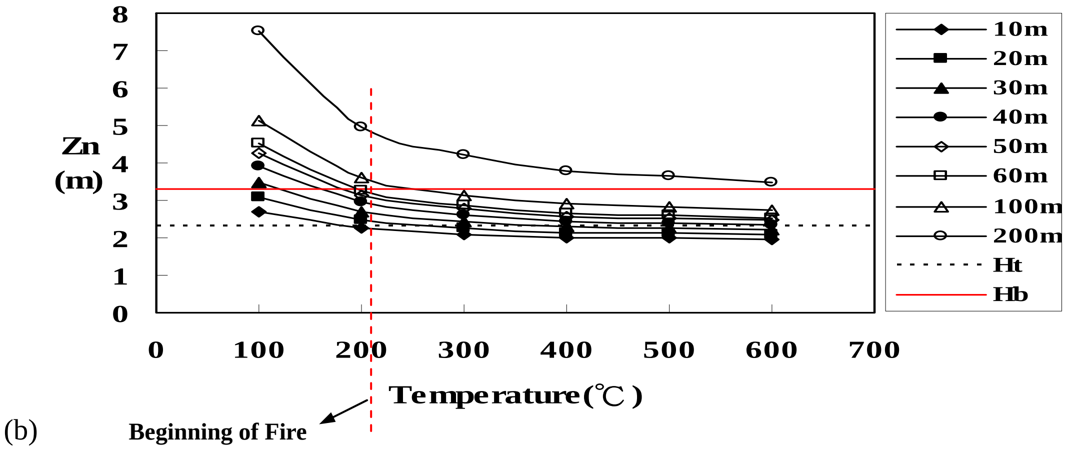
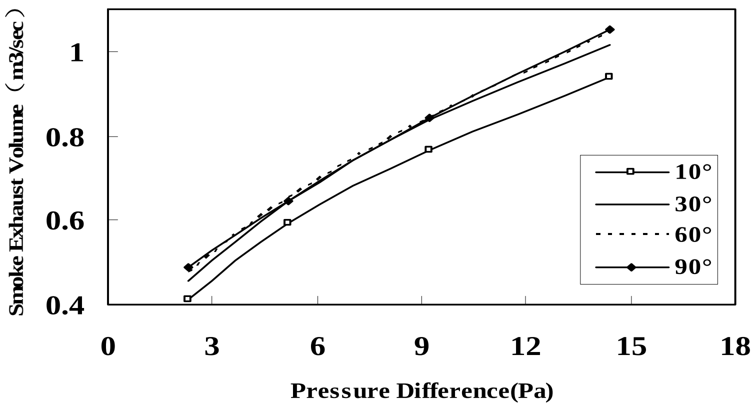


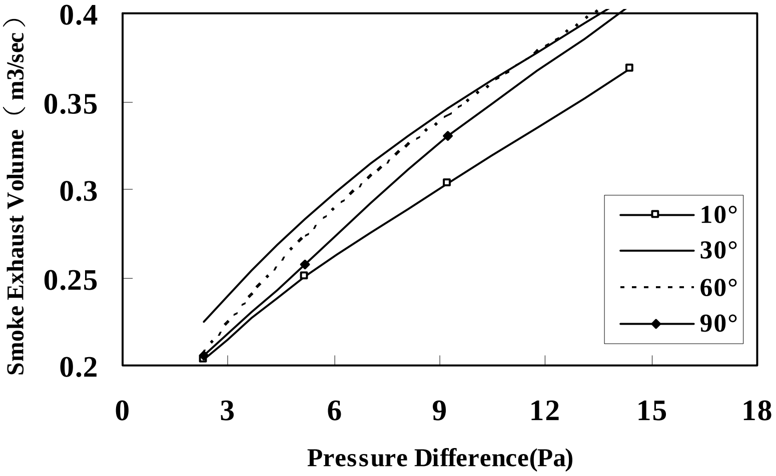
FIGURE 6. The flow direction at different natural heights for a natural vent/window at (a) 75 cm down below ceiling and (b) 20 cm down below ceiling

Design of Natural Smoke Exhaust Vent/Window

In Taiwan's building code the natural smoke exhaust vent/window is always closed at normal time. The vent/window shall be opened when the fire signal connected to the vent/window. Of course, the vent/window also can be opened by manually. However, no exact opening width is specified by regulations. Basically, the opening width of natural smoke vent/window will influence the performance of smoke exhaust performance. Therefore, a wind tunnel experimental program was conducted to examine the pressure difference inside and outside vents/windows for different opening widths. Four different opening angles of vent/window, 10, 30, 60 and 90 degrees were used for the experimental program. Behind the vent/window, an air supply fan provided appropriate air volume through air duct against the air direction of wind tunnel. Therefore, the pressure difference may be adjusted between the front and the rear of vent/window. Test results are depicted in Figs. 7 (a) and (b) for 2 m/s and 3 m/s air velocity of wind tunnel, respectively. Following the Taiwan's weather data, the pressure difference may also stand for the building height technically. According to the test data, the natural smoke exhaust vent/window can have effective function for the opening angle greater than 30 degrees. However, for higher wind velocity or less hot smoke buoyancy the vent/window may need wider opening angles. In Fig. 7 (b) when the air velocity of wind tunnel increased to 3 m/s the 90 degree opening angle case did not have the maximum smoke exhaust performance. It is believed that some degree of obstacle in front of smoke vent/window may provide better smoke exhaust performance for higher wind velocity cases. When fire occurred in tall buildings, the 30 to 60 degrees opening angles are suggested for a successful and effective natural smoke exhaust vent/window system.



(a)



(b)

FIGURE 7. The relationship between smoke exhaust volume and pressure difference (building height) for (a) 2 m/s velocity in wind tunnel and (b) 3 m/s velocity in wind tunnel

CONCLUSIONS

Many aspects will influence the smoke exhaust system of tall buildings, such as buoyancy force, mechanical ventilation, stack effect, and wind effect etc. The wind effect will play an important role on natural smoke exhaust systems of tall buildings. The wind tunnel test results provide useful data for evaluating the performance of smoke exhaust system in tall buildings of Taiwan under the existing building code. For considering the wind pressure around buildings some useful conclusions may provide in this study.

(1) For residential areas the smaller vent size may provide higher exhaust smoke velocity that will provide higher pressure to overcome the wind pressure. The wind pressure will increase with the building height, therefore, the smoke exhaust vents are recommended to install upon roof for better smoke exhaustion efficiency.

(2) For a smoke vent/window beneath 80 cm of ceiling and the smoke temperature at 200^{o} C, the smoke can exhaust through out the building at 60 m building height. Notwithstanding, when the smoke temperature increases to 300^{o} C the smoke can exhaust through out the building at 100 m building height.

(3) For the elevator lobby area, the location smoke exhaust vent/window was discussed in this paper. When the vent/window location moves from 75 cm to 20 cm down below the ceiling the effective building height that hot smoke may exhaust through the vent/window shifts from 30 m to 60 m. The natural smoke exhaust vent/window install near the ceiling as possible may obtain optimal smoke exhaust effect.

(4) In considering the design of natural smoke exhaust vent/window, the 30 to 60 degrees opening angles are suggested for a successful and effective natural smoke exhaust vent/window for tall buildings.

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