Design Method of Vertical Ventilation with Wind Chimney on Roof Driven by Wind and Buoyancy

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Abstract

The calculation system for vertical ventilation with wind chimney on the roof driven by wind and buoyancy is presented and the necessary data is measured. The calculation system is based on the "pressure – airflow rate relationship (Pressure -Volume curve: P-V curve)" and the local velocity and static pressure at the point of chimney top. The P-V curves were measured by wind tunnel test for some typical shapes of wind chimney top. It is turned out that the effect of upper wind velocity can be eliminated by normalization of the pressure at chimney neck and airflow rate through the chimney. The number of tested models are six : simple outlet, two types of wind-break plates, two types of horizontal duct, rainproof type.

Keywords: Wind chimney, Vertical ventilation, Wind tunnel test, Pressure - Volume curve

1. Introduction

In urban area, the cross ventilation through windows is not necessarily possible. In such cases, vertical ventilation using devices such as chimney is effective. In this paper, the chimney ventilated by wind force is named “wind chimney” as a device for natural ventilation in building superior to simple side windows. In most cases, wind chimney will be assisted by buoyancy caused by the heat emission inside the room.

Nevertheless, there is no established calculation system that enables us to design the wind chimney. In general, wind pressure coefficient is used for the calculation of ventilation rate through windows of a building, but it is not appropriate to apply wind pressure coefficient to the chimneys exposed to natural wind. It is because the mutual action between natural wind and shape of chimney top is quite complicated, and for example the suction effect on the pressure loss through the overall chimney can change depending on wind direction and airflow rate of chimney. The design method of wind chimney, therefore, is quite necessary.

So, the objectives of this study are to present the equations to predict the airflow rate of vertical chimney based on “Pressure – airflow rate relationship” (Pressure -Volume curve: *P*-*V* curve) and to measure Pressure -Volume curve representative of the ventilation characteristics of each wind chimney with different top-shape by wind tunnel test.

2. Methods

2.1 Equations for calculation of airflow rate of wind chimney

In this section, basic equations to calculate the airflow rate of chimney will be introduced. Based on the equations previously presented by Ishihara[1)], the static pressure at the chimney neck (base of the chimney, see **Fig.1**) p_c [Pa] can be defined as the function of airflow rate of chimney Q [m^3/s], local wind velocity around chimney top V_L [m/s], wind direction angle to the chimney θ [degree]. So the following equation can be written.

$$p_c = f(Q, V_L, \theta) \qquad \text{(Eq. 1)}$$

This function f in **Eq.1** is representative of the characteristics of each chimney, which depends on the shape of chimney top. It is essential to determine this function from the experiment in wind tunnel or CFD analysis and so on.

Using this equation and Bernoulli's principle, the following equation can be derived,

$$p_c = f(Q, V_L, \theta) - (\rho_o - \rho_i) g h_c + C_L \frac{\rho_o}{2} V \qquad \text{(Eq. 2)}$$

where ρ_o and ρ_i is the density of outdoor air and air inside chimney [kg/m^3], g is gravitational acceleration [m/s^2] (=9.8), h_c is chimney height above chimney neck [m], C_L is local pressure coefficient in the air at chimney top position, V is upper wind velocity independent of air stream around building. (see **Fig.1**) Here, it should be noted that C_L is not the wind pressure on the wall of chimney or building, but the static pressure in the air at the position of chimney top normalized by the dynamic pressure of natural wind at the height of chimney top.

2.2 Measurement of pressure-volume curve using wind tunnel test

In order to measure the *P-V* curve of different chimney types, wind tunnel test was conducted. Scaled model of various chimneys were made, and they were installed on the floor of wind tunnel. **Fig.2** shows the cross-section of test models of chimney, and **Fig.3** shows the appearance of each model. Model A is a simple chimney type, and Model B & C is the simple chimney with wind barrier in front of openings in vertical walls at chimney top. Model C has base plate at the bottom of wind barrier of Model A. Model D allows wind enter the horizontal duct placed on the top of Model A. Model E is the improved type of Model D whose horizontal duct has a constricted section area at the chimney top to introduce Venturi effect. Model F is the designed type for a real building of a college in Japan. This model has an inside opening with a shutter at the bottom of chimney, which can be controlled automatically to prevent rain infiltration.

After the chimney model was set on the floor of wind tunnel, then the air is supplied though flexible duct by fan installed outside the wind tunnel (see **Fig. 4**). The airflow rate was measured by orifice flow meter, and the static pressure at each chimney neck was measured by micro differential pressure gauge. In Fig.5, the details of the neck of chimney model are shown. Velocity of approaching wind is 5 m/s, and the velocity distribution is uniform. Turbulent intensity of approaching wind is less than 0.5%. The reference static pressure and reference dynamic pressure are measured by pitot tube at the center of tunnel section. The height of pitot tube is 0.9m above the floor. Base duct with the length of 20cm was attached to each chimney to place the chimney top at higher position (see **Fig.3**). Sampling frequency is 100Hz, and the pressure and velocity data for 30 seconds were analyzed to obtain mean values. Table 1 shows the experimental conditions, that is, tested wind direction angle defined in Fig.2 for each chimney model.

3. Results

3.1 Effect of upper wind velocity on Pressure-Volume curve (*P-V* curve)

Only in the case of Model A and wind direction angle 0 degree, three wind velocities were tested. The relationship between airflow rate and static pressure at chimney neck is presented in Fig.6(1). On the other hand, in Fig.6(2), airflow rate was normalized by the product of section area of chimney neck and upper wind velocity, and static pressure was normalized by dynamic pressure of upper wind. From these two graphs, *P-V* curves of different wind velocity can be presented by representative one curve independent of velocity effect for each chimney type and wind direction angle. This curve will be called normalized P-V curve of a chimney.

3.2 Comparison of flow characteristics of different chimney top

Fig.7 shows normalized *P-V* curves of the tested chimneys. These curves were derived from the test data in the case that the upper wind velocity is 5 m/s. Some curves for different wind direction angles are drawn in each graph. It is important the static pressure of chimney neck at zero velocity of chimney neck means wind pressure coefficient of the chimney top. If this value of a chimney has large negative value, such chimney is able to induce strong suction effect utilizing dynamic pressure of natural wind. The *P-V* curves of Model A for three wind directions shows relatively low neck pressure at any normalized velocity at chimney neck, and the wind angle of 45 degrees shows lowest neck pressure. The lower the pressure at chimney neck is, the smaller the pressure loss through the chimney becomes.

At Model B, the type with wind barrier, the neck pressure change hardly and quite stable against neck velocity. This tendency is supposed to be brought by the airflow between the chimney top and wind barrier surrounding the chimney openings. At Model B, the wind angle of 45 degree also shows the lowest neck pressure, but the difference due to wind angle seems smaller than that of Model A.

At Model C, the inclination of *P-V* curve is rather larger than that of Model B, but the neck pressure shows the lowest value in these three models, Model A, B &C. It can be said that the largest top area causes blocking effect in the natural wind and makes the largest negative pressure at chimney top.

In the case of Model D, the pressure loss depends on the wind direction angle. From the graph, at v/V >0.3, the order of pressure loss is 0° or 22.5°, 45°, 67.5°, 90°. The wind direction of 90° can produce the lowest pressure due to strong side suction made by large section area of the chimney top. In the case that the approach wind can enter the chimney top without obstacles at wind direction angle of 0°, blocking effect of the airflow in the confined rectangular vent can produce larger pressure loss than the other wind angle.

These tendencies are also true of Model E, and the difference of wind angle is larger than that of Model E. This is, of course, affected by Venturi effect due to the constricted section area of rectangular vent.

Model F is an example of real chimney installed on the roof of school building in Kobe, Japan (see **Fig.8**). These chimneys are connected to the large lecture halls on the 3rd floor of 6-story building. Each lecture hall have two chimneys and 300 students in the class, and the hall will be ventilated by both wind-force and buoyancy. As is seen in Fig.2, Model F has a small opening inside to protect the vertical duct from heavy rain. This opening will produce large pressure loss in P-V curve of **Fig.7**, which seems like a quadratic function. This means total pressure loss coefficient of chimney is almost constant, because of the small opening inside the chimney. The difference by wind direction angle is relatively small. Although Model F was designed with the priority of aesthetic point of view, it is made clear from **Fig.7** that this model is not superior to other chimney models from the viewpoint of ventilation capacity.

From **Fig.7**, it is concluded that Model C is the best in respect of ventilation capacity utilizing wind force, because this chimney has the lowest neck pressure in wide range of neck velocity. In this paper, only 6 models were examined, but there might be some better shapes of chimney top. It is desired that many useful data of P-V curves of wind chimney will be obtained by further study.

4. Conclusions

The concluding remarks made clear in this paper are as follows:

1) The calculation of airflow rate of wind chimney is enabled by identifying the relationship between airflow rate of chimney and the pressure at the neck of chimney. This relationship is called Pressure-Volume curve (*P-V* curve).
2) The modified Bernoulli's equation was introduced to calculate the airflow rate of chimney, taking account of local pressure coefficient C_L in the air at chimney top position.
3) Six models of chimney with different shapes were tested by supplying air through the chimneys in a wind tunnel with approach wind of 5 m/s to measure the *P-V* curves. This experiment was turned out to be useful to know the ventilation characteristics of wind

chimney.

4) By normalizing *P-V* curves, different *P-V* curves can be presented by representative one curve independent of velocity effect for each chimney type and wind direction angle. This is the relationship between the velocity at the chimney neck divided by approach wind velocity and the static pressure at the chimney neck divided by dynamic pressure of approach wind.

5) Among six chimney models, two models with large wind barriers have excellent capacity in comparison with the other models. Especially Model C with wind barriers whose bottom is covered with plates.

Acknowledgments

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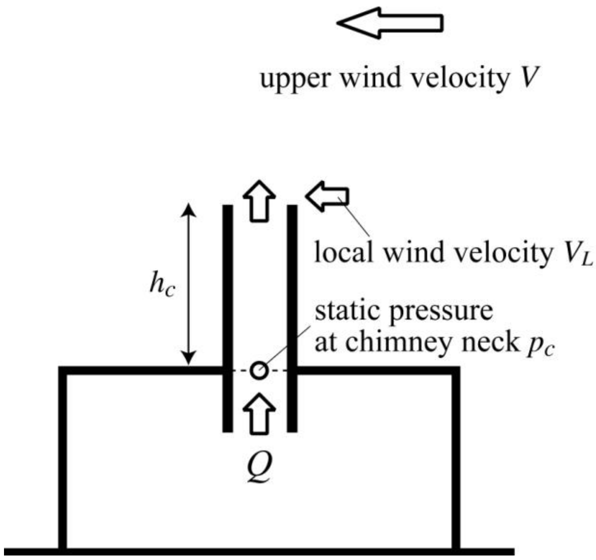


Fig. 1 Explanation of variables

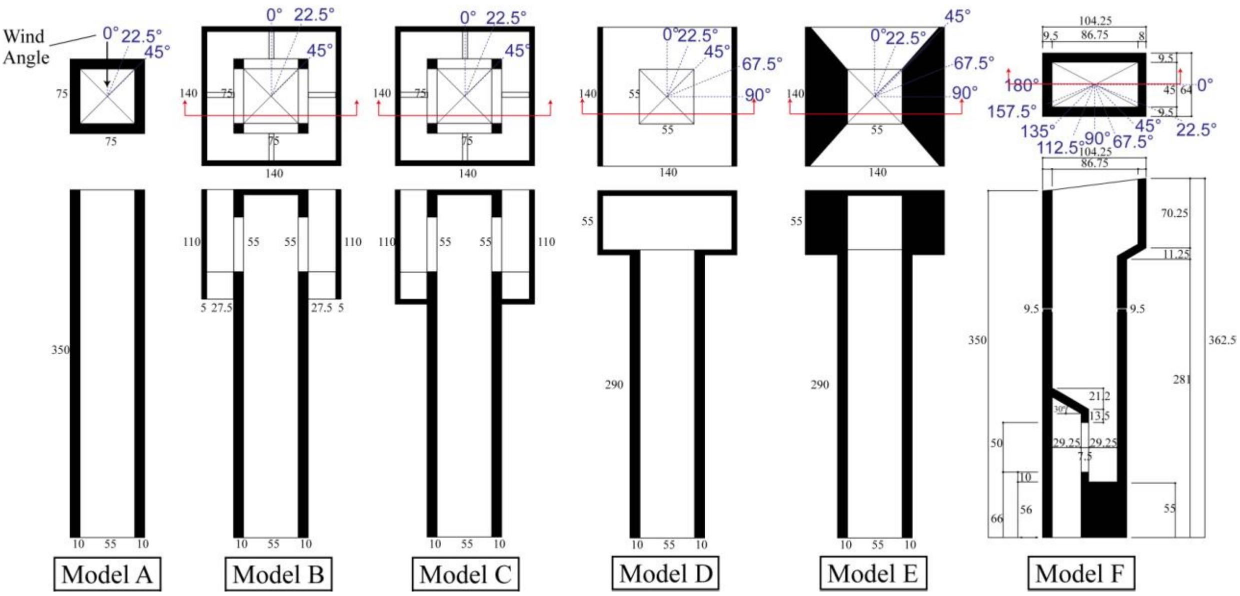


Fig. 2 Cross-section of test models of wind chimney

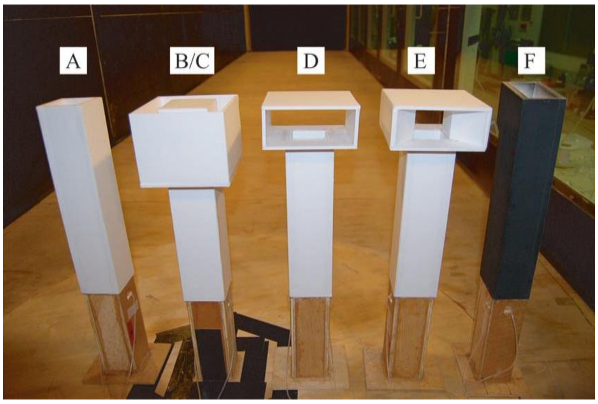


Fig. 3 Tested chimney models with different tops

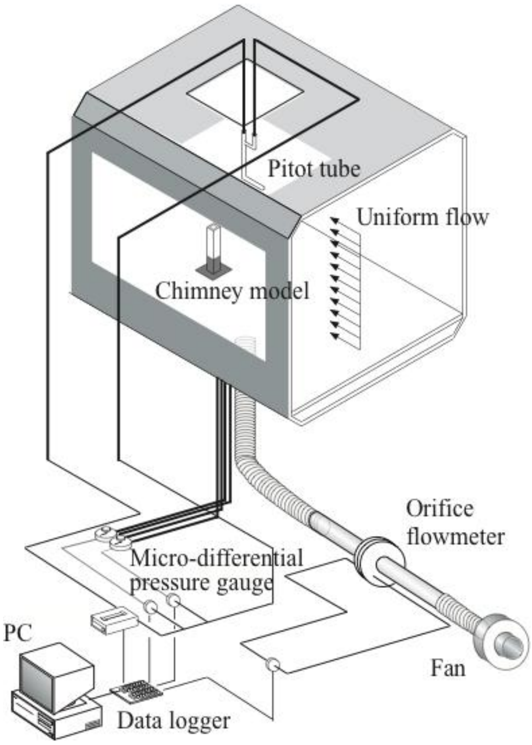


Fig.4 Experimental setup

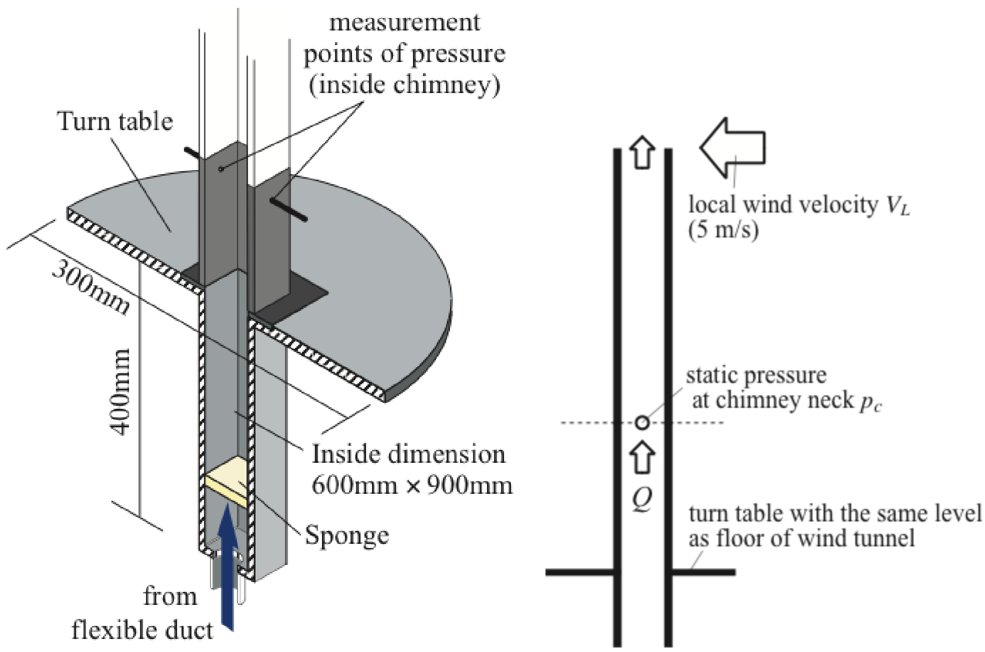
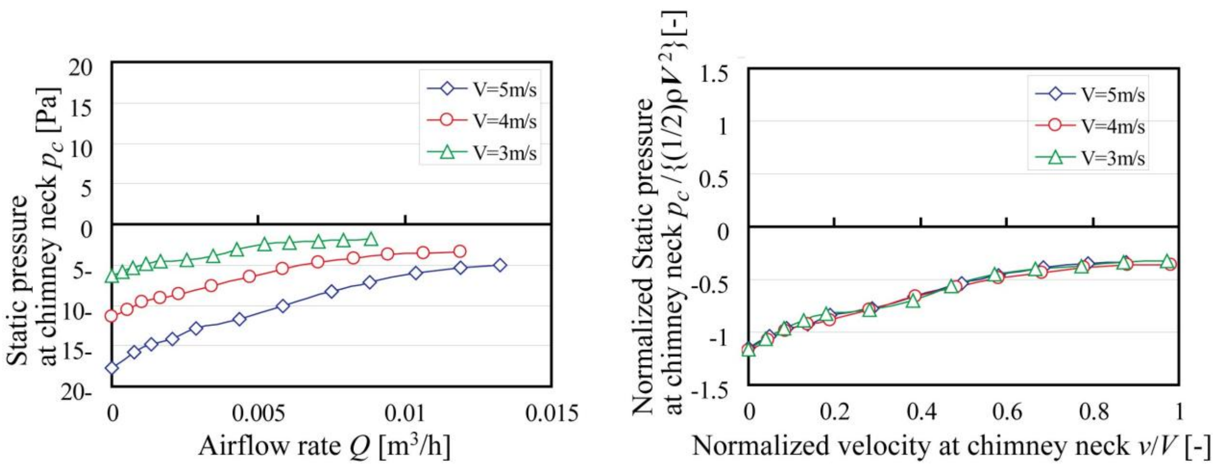


Fig.5 Measurement point of pressure at the neck of chimney



a) Pressure-volume curves b) Normalized pressure-volume curves

Fig.6 Relation between Airflow rate and static pressure at the neck of chimney (Chimney : Model A, wind direction : 0 degree)

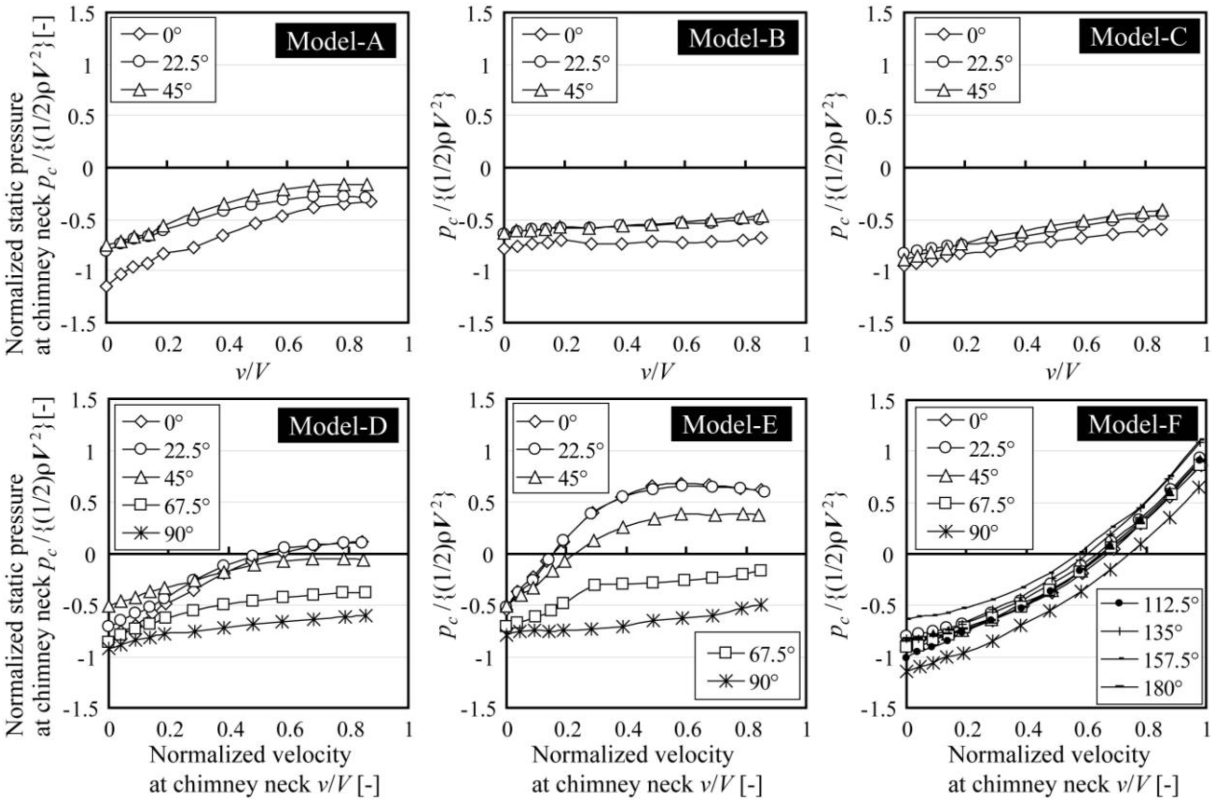


Fig. 7 Comparison of flow characteristics of each chimney

Fig.8 Appearance of chimney (Model F) in real building

Table 1 Experimental conditions

Shape of chimney top	Wind direction angle [degree]
A (simple outlet)	0, 22.5, 45
B (wind-break plate)	0, 22.5, 45
C (wind-break plate with bottom plate)	0, 22.5, 45
D (horizontal duct)	0, 22.5, 45, 67.5, 90
E (horizontal duct introducing contraction flow)	0, 22.5, 45, 67.5, 90
F (rainproof : example applied to a real building)	0, 22.5, 45, 67.5, 90, 112.5, 135, 157.5, 180