Natural Ventilation in Building

Chirdpun Vitooraporn
Building Technology & Environment Laboratory
Mechanical Engineering Department, Faculty of Engineering, Chulalongkorn University
Phayathai Rd., Phatumwan Bangkok 10330
Tel. 218-6622 Fax 252-2889 E-mail: chirdpun@hotmail.com

Abstract

This article provides an explanation on the natural ventilation in the building which is caused by two mechanisms, ie. wind effect and stack effect. Other parameters which involved in these two mechanisms are also presented. This is to distinguish the different between these two mechanisms. Equations involved are also presented to clarify the effect of those parameters. The method to calculate the ventilation rate from each mechanism is presented as well.

1. Introduction

Ventilation in building is necessary to remove any undesirable odours and contaminants as well as to replace the carbon dioxide produced in the space by supplying an adequate amount of oxygen. Ventilation is not only necessary for the occupied space but also for the unoccupied space to ensure that there is no possibility of vapours forming an dangerous or explosive mixture.

There are two ways of building ventilation: by natural ventilation in which openings such as windows, ventilating shafts or ventilators are used to allow outside air to enter and inside air to leave the building. Pressure different between outside air and inside air is a driving mechanism for the air to enter and leave the building. Another way is by mechanical ventilation in which fan is used to control the amount of air to flow in and out. Therefore ventilation system in general can be done as follow;

1. Using natural ventilation for both air flowing in and flowing out.
2. Using natural ventilation for air flowing in and mechanical ventilation for air flowing out.
3. Using mechanical ventilation for air flowing in and natural ventilation for air flowing out.
4. Using mechanical ventilation for both air flowing in and air flowing out.

This article presents only the ventilation system that uses natural ventilation.

2. Natural Ventilation

Pressure different between inside air and outside air is caused by 2 driving forces, i.e.

1. The pressure on the face of a building due to the rapid deceleration of the wind on the outside surface. This is called the wind effect.
2. The buoyancy effect due to temperature difference between the outside air and inside air. This causes the different in density between the outside air and inside air. This effect is called the stack effect.

3. Wind Effect

When winds flow across a building, the air is forced to rest on the front face of the building causing a pressure on the face of the building higher than the pressure of the undisturbed air stream. While at the back of the building, the pressure on the surface of the building is lower than the pressure of the undisturbed air stream. Moreover, in case of flat roof building, the air pressure on the roof is lower than the air pressure of the undisturbed air stream. Due to this non uniform pressure distribution around the building, it is necessary to use the average value of the overall pressure acting on the building surface to calculate for the natural ventilation. This average pressure at the building surface is proportion to the velocity pressure. The velocity pressure can be calculated by using the Bernoulli equation;

$$P_V = \rho U_H^2/2 \qquad (1)$$

when P_V = velocity pressure

ρ = air density

U_H = wind velocity at the maximum height of building surface that faces the wind

ASHRAE Fundamentals 1993 recommends to calculate this wind velocity by using the reference wind velocity, U_{REF}, from wind velocity measured at the weather station nearest to the building location, U_{MET}, and the terrain of the area, A_O as shown in equation (2).

$$U_{REF} = A_O U_{MET} \qquad (2)$$

Where A_O can be found from figure1.

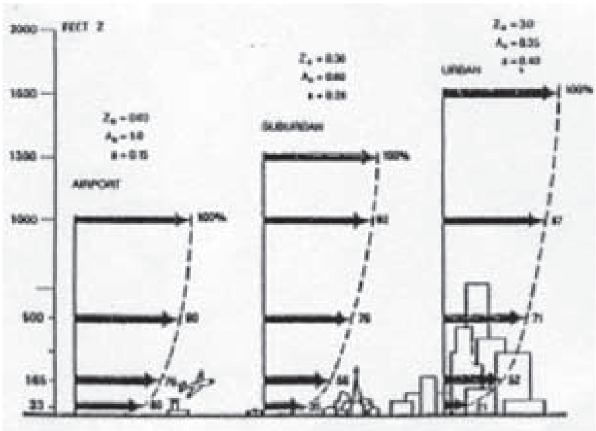

Figure 1 *Wind velocity distribution at various areas (1)*

However, in general U_{MET} is measured at the reference height, H_{REF}, for example wind velocity at the weather station in the airport is measured at 9.9 m. high in flat and open surface area. Therefore the required wind velocity, U_H, at the building height must be calculated based on the reference height that measured wind velocity and the distribution of wind velocity in the vertical direction form ground surface in order to find the average wind velocity at that area as shown in equation (3)

$$U_H = U_{REF}(H/H_{REF})^a \quad (3)$$

where a is the index for wind velocity distribution from fig. 1

The Chartered Institution of Building Services Engineers (CIBSE) also recommends another equation to calculate the required wind velocity in the similar manner as shown in equation (4)

$$U_H = U_M K_Z Z^a \quad (4)$$

where

U_M = average velocity at a height of 10 m. in open country.

Z = height at required velocity.

K_Z and a = parameters dependent on the terrain as shown in table 1.

Table 1 Values of K_Z and a in equation (4)

Terrain	K_Z	a
Open, flat country	0.68	0.17
Country with scattered windbreaks	0.52	0.20
Urban	0.35	0.25
City	0.21	0.33

The non uniform air pressure as mentioned earlier depends on the wind direction and wind velocity and will vary from day to day. Davenport and Hui (1982) has shown the coefficient of the average pressure, C_p, occurred at the surface of high building (the height is 3 times of the width that faces the wind) due to the different wind direction as shown in figure 2. Holmes (1986) has shown the same coefficient for low rise building as shown in figure 3. The coefficient of the average wind pressure is defined as shown in equation (5).

$$C_P = (P - P_O)/0.5\,\rho U_H^2 \quad (5)$$

Where P = average pressure at any position on building surface.

P_O = wind pressure in the undisturbed air stream.

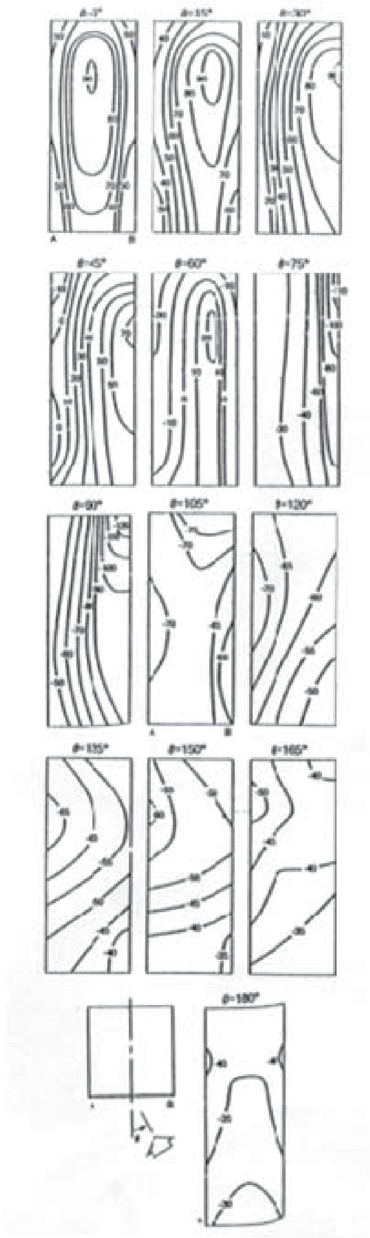

***Figure 2** Coefficient of average pressure (C_Px100) on high building surface at different wind direction. (1)*

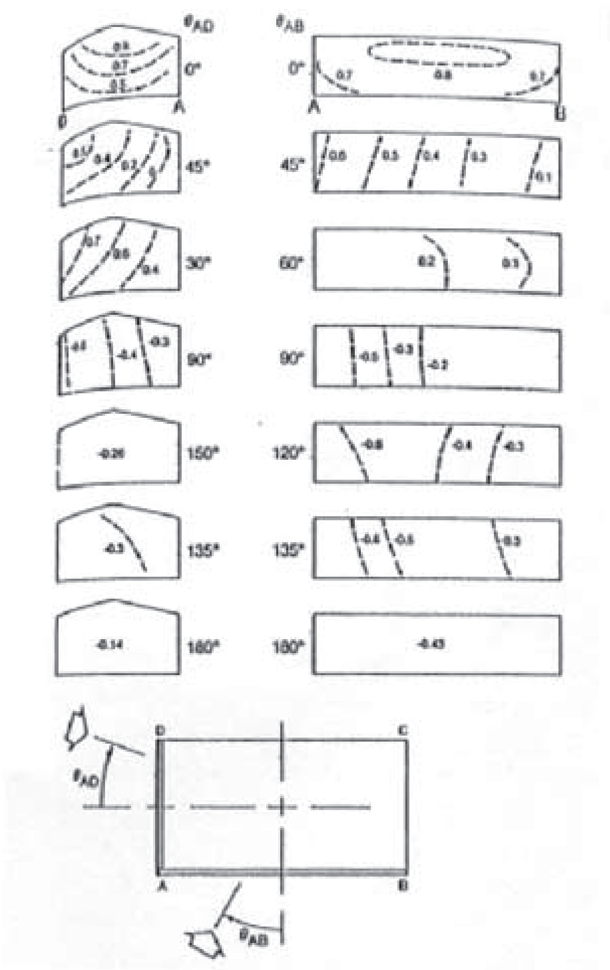

Figure 3 Coefficient of average pressure, C_P, on low building surface from different wind direction (1)

4. Ventilation Calculation from Wind Effect

To calculate the natural ventilation from wind effect using data mentioned earlier, we begin by calculating the volumetric air flow rate through the opening as shown in equation (6)

$$Q = C_D A U \quad (9)$$

Where

Q = volumetric flow rate.

A = cross section area of the opening.

U = air velocity leaving the opening.

C_D = discharge coefficient.

Where velocity U can be calculated from

$$\rho U^2/2 = \Delta P \quad (7)$$

When

ΔP = pressure drop across the opening

Substituting velocity from eq. (7) into eq. (6)

$$Q = C_D A (2\Delta P/\rho)^{0.5} \quad (8)$$

Assuming that pressure drops across the openings at the same building surface are all equal then for many openings on the same building surface the total volumetric air flow rate is equal to

$$Q = C_D \Sigma A (2\Delta P/\rho)^{0.5} \quad (9)$$

When ΣA = total cross section area of the opening on the same building surface.

For air entering the building, the volumetric air flow rate, Q_1, is

$$Q_1 = C_D \Sigma A_1 \{2(P_1 - P_I)/\rho_1\}^{0.5} \quad (10)$$

Fore air leaving the building, the volumetric air flow rate, Q_2, is

$$Q_2 = C_D \Sigma A_2 \{2(P_I - P_2)/\rho_2\}^{0.5} \quad (11)$$

Where

P_1 = air pressure entering the building.

P_2 = air pressure leaving the building.

P_I = air pressure inside the building.

A_1 = cross section area of the opening where air

A_2 = cross section area of the opening where air

ρ_1 = density of air entering the building.

ρ_2 = density of air leaving the building.

From mass balance at the steady state condition; $Q_1 = Q_2 = Q_W$, therefore equation (10) and (11) can be rearranged by setting $\rho_1 = \rho_1 = \rho$

$$P_1 - P_2 = (\rho Q_W^2/2C_D^2)[1/(\Sigma A_1)^2 + 1/(\Sigma A_2)^2] \quad (12)$$

From equation (5), we get

$$C_{P1} = (P_1 - P_O)/0.5\rho U_H^2 \text{ and } C_{P2} = (P_2 - P_O)/0.5\rho U_H^2$$

Therefore $$P_1 - P_2 = (C_{P1} - C_{P2})0.5\rho U_H^2 \quad (13)$$

Substitute $P_1 - P_2$ from equation (13) into equation (12)

$$(C_{P1} - C_{P2})0.5\rho U_H^2 = (\rho Q_W^2/2C_D^2)[1/(\Sigma A_1)^2 + 1/(\Sigma A_2)^2] \quad (14)$$

Rearrange equation (14), the volumetric air flow rate can be calculated as shown below

$$Q_W = C_D(\Sigma A_W)U_H(C_{P1} - C_{P2})^{0.5} \quad (15)$$

Where $1/(\Sigma A_W)^2 = 1/(\Sigma A_1)^2 + 1/(\Sigma A_2)^2$

Equation (15) can be used to calculate the ventilation rate inside the building via openings resulted from the wind effect. This is done by calculating U_H from equation (3) or (4). C_P can be found from figure 2 and 3. For C_D, CIBSE recommends to use the value of 0.61 which provides an accurate answer for ventilation via the opening.

5. Opening Location for Ventilation Consideration

Figure 2 and 3 should be used when considering the location of the opening for ventilation purpose. This will help pulling in the air stream into the building (positive pressure) and ventilating the air stream out of the building (negative pressure). It also avoids any hindrance that might occur from the air stream. From figure 2 and 3 one can find out that both positive and negative pressure could occur on the same building surface and the variation is quite wide. Therefore the consideration should emphasis where the coefficient of the average pressure is not much varied for different wind directions. This is because the building should have a good ventilation no matter what wind direction is. Moreover the value of C_P depends more on wind direction than location of the opening. ASHRAE recommends to avoid locating the opening at the corner of the building.

6. Stack Effect

Another mechanism for natural ventilation is resulted from the stack effect which happened due to the air density different between inside air and outside air. The different in pressure is then occurred and hence the air movement. The hot air goes up and is replaced by the cool air. The pressure distribution inside the building is varied according to the building height. The building height where the pressure inside the building is equal to the pressure outside the building is called the neutral pressure level, NPL, (Tamura & Wilson, 1966, 1967). In summer, at the location above the NPL, the pressure inside the building is higher than the pressure outside. At location below the NPL, the outside pressure is higher resulted in the flow of air stream coming in from the lower section of the building.

The pressure different due to this effect can be written as follow;

$$\begin{aligned}\Delta P_S &= C_2(\rho_O - \rho_I)g(H - H_{NPL}) \\ &= C_2 \rho_I g(H - H_{NPL})(T_I - T_O)/T_O \end{aligned} \quad (16)$$

Where ΔP_S = pressure different due to stack effect, WG in inch

ρ = air density ≈ 0.075 lb_M/ft^3 for inside condition of the building

g = acceleration due to gravity = 32.2 ft/s^2

H = height at the required location, ft

H_{NPL} = height at neutral pressure, ft

T = average absolute temperature, ^{O}R

C_2 = unit conversion = 0.00598

Subscript I = inside O = outside

ASHRAE Fundamental 1993 provides the estimated value for pressure different due to the stack effect as follow;

$$\Delta P_S = 2.7 x 10^{-5} (H - H_{NPL}) \Delta T \quad \text{WG in inch} \quad (17)$$

Where ΔT = temperature different between inside and outside

From equation (16) and (17), the location of NPL is an important parameter in calculating the pressure different which leads to the volumetric air flow rate calculation. NPL location at zero wind velocity is a variable dependent on the building structure which depends on the orientation of each opening along the vertical direction. There are many researches that try to calculate the NPL height based on several constraints of the opening inside the building. Tamura & Wilson (1966, 1967) concluded that NPL location for high building is at 0.3 to 0.7 of the overall building height. Shaw & Brown (1982) studied the NPL location of the residential housing with chimney. They found that the NPL location is more than half of the housing height. If there is a combustion inside the chimney, the NPL location may be even higher or higher than the ceiling level.

7. Ventilation Calculation from Stack Effect

Consider building with 2 opening areas, A_1 and A_2, located at different height Z as shown in figure 4.

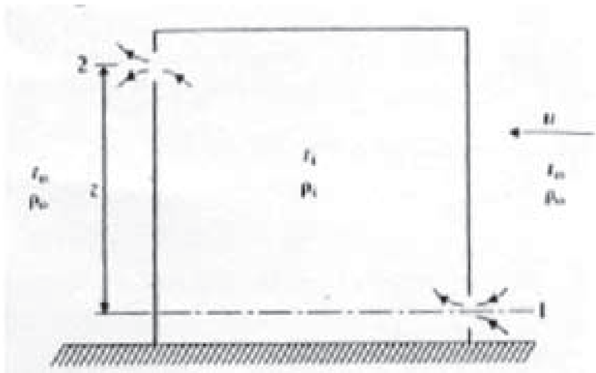

Figure 4 Building with 2 openings

Neglecting the wind effect, the pressure outside the building can be found from

$$P_{O1} = P_{O2} + g \rho_O Z \quad (18)$$

Where

P_{O1} = pressure outside the building at opening 1

P_{O2} = pressure outside the building at opening 2

ρ_O = average air density outside the building

Z = different height between these 2 opening

The pressure inside the building can be calculated from

$$P_{I1} = P_{I2} + g \rho_I Z \quad (19)$$

Where P_{I1} = pressure inside the building at opening 1

P_{I2} = pressure inside the building at opening 2

ρ_I = average air density inside the building

Subtract equation (19) from equation (18)

$$P_{O1} - P_{I1} = gZ\Delta\rho - (P_{I2} - P_{O2}) \quad (20)$$

From mass balance at steady state condition, the air mass flow rate at opening 1 is equal to the air mass flow rate at opening 2. Therefore

$$\rho_O Q_1 = \rho_I Q_2 \quad (21)$$

Substitute Q_1 and Q_2 from equation (10) and (11) into equation (21) and use the appropriate value of pressure and opening area, then

$$\rho_O C_D A_1 \{2(P_{O1}-P_{I1})/\rho_O\}^{0.5} = \rho_I C_D A_2 \{2(P_{I2}-P_{O2})/\rho_I\}^{0.5} \quad (22)$$

Rearrange the equation above

$$P_{I2}-P_{O2} = (P_{O1}-P_{I1})\{\rho_O (A_1)^2/\rho_I (A_2)^2\} \quad (23)$$

Substitute into equation (20)

$$P_{O1} - P_{I1} = gZ\Delta\rho - (P_{O1}-P_{I1})\{\rho_O (A_1)^2/\rho_I (A_2)^2\} \quad (24)$$

Rearrange the above equation

$$P_{O1} - P_{I1} = (gZ\Delta\rho)/[1+\{\rho_O (A_1)^2/\rho_I (A_2)^2\}] \quad (25)$$

Equation 25 can be used to calculate the ventilation rate due to the stack effect as follow;

$$Q_S = C_D A_1 \{2(P_{O1} - P_{I1})/\rho_O\}^{0.5} \quad (26)$$

Using $P_{O1} - P_{I1}$ from equation (25)

$$Q_S = C_D\{2gZ\Delta\rho/\{\rho_O[1/(A_1)^2 + \rho_O/(\rho_I A_2^2)]\}\}^{0.5} \quad (27)$$

Equation (27) can be transformed into a more handy form by considering the following assumptions;

a. The average air density, both inside and outside the building, is equal.

b. $\Delta\rho/\rho = \Delta T/T$ when T = average absolute temperature for inside and outside air, ΔT = average different temperature for inside and outside building.

Using these two assumptions, equation (27) can be reduced to

$$Q_S = C_D A_N \{2gZ\Delta T/T\}^{0.5} \quad (28)$$

Where $1/A_N^2 = 1/A_1^2 + 1/A_2^2$

For building with more than 2 openings, the equation can be applied by replacing A_1 with ΣA_1 and A_2 with ΣA_2.

8. Conclusion

As presented in this article, one can see that there are many parameters that involved in natural ventilation, i.e. wind direction, height different of the opening, opening location, different in density and temperature. Further study for the results from natural ventilation either from wind effect or stack effect is still needed in order to understand the mechanism effect from both. Equations shown in this article only approximate the amount of air flow rate. In fact, air flow pattern around the building and building shape play an important role in determining the location of positive or negative pressure when the air blows pass the building. Even more complicated is that when these two effects simultaneously occur. This leads to a more difficulty in finding the actual ventilation rate because when this happens, it can be added up or cancelled up each other dependent on the location of the opening and wind direction.

9. Reference

1. ASHRAE Fundamental 1993.
2. T.D. Eastop & W.E. Watson, Mechanical Services for Building, Longman, 1997.
3. Davenport, A.G. and H.Y.L. Hui, "External and internal wind pressures on cladding of buildings", Boundary Layer Wind Tunnel Laboratory, The University of Western Ontario, London, Ontario, BLWT820133, 1982.
4. Holmes, J.D., "Wind loads on low rise buildings: The structure and environmental effects of wind on building and structures", Chapter 12, Faculty of Engineering, Monash University, Melbourne, Australia, 1986.
5. Shaw, C.Y. and W.C. Brown, "Effect of a glass furnance chimney on the air leakage characteristic of a two story detached house", 12.1 Proceeding of the 3rd IEA Conference of the air filtration centre, London, 1982.
6. Tamura, G.T. and A.G. Wilson, "Pressure different for a nine story building as a result of chimney effect and ventilation system operation", ASHRAE Transactions 72(1):80, 1966.
7. Tamura, G.T. and A.G. Wilson, "Pressure different caused by chimney effect in three high buildings", ASHRAE Transactions 73(2):II.1.1, 1967.