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VENTILATION RATE OF AN ENCLOSURE WITH A SINGLE OPENING EXPOSED TO NATURAL WIND

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In the present design method of natural ventilation of a building, there is a problem that the air flow rate through a single opening settled on an airtight room can not be predicted precisely. It is well known that such a room is ventilated to some extent because of turbulence of natural wind. As one of the prediction method of ventilation rate through a single opening, the theory based on mixing layer was presented by P.R.Warren. The aim of this study is to verify the usefulness of this method and to make the limit of application evident. For this purpose, wind tunnel test is conducted.

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INTRODUCTION

In the present natural ventilation design of a building, the air flow rates through windows or ventilating openings are generally calculated by the theory which is based on the pressure difference across the opening. There is , however, a problem in this theory that the air flow rate forced by wind through a single opening settled on the airtight room will be computed at zero, nevertheless it is known that such a room is ventilated to some extent because of the turbulence of natural wind. This phenomenon was pointed out in the past (1,2) and some fundamental studies were carried out in experimental and theoretical way. The authors have studied this problem in order to establish more realistic design method of natural ventilation. (3) A cubic model enclosure (60*60*60 cm) with a single circle opening was exposed to artificial wind with various turbulence made by fan and the ventilation rate were measured under many conditions. In consequence, the outline of the effect of some factors (mean wind velocity, turbulent intensity, opening area, incident angle of wind) on the air flow rate through a single opening is made clear and it turned out that the air flow rate can be predicted by the theoretical model of pulsation at the opening if the incident angle of wind is zero and the stagnant point is situated at the center of opening. It, however, also turned out that it is impossible to predict the air flow rate correctly by such a theoretical model based on the wind pressure on the opening if the incident angle is away from 0, because the calculated value of air flow rate can not account for the change of air flow rate caused by the change of incident angle of wind. As a method to predict the change of air flow rate induced by the change of incident angle of wind, the turbulent diffusion theory of mixing layer by P.R.Warren (4) can be cited. This equation to calculate the air flow rate through a single opening was presented as shown in Table 1. For the flow is parallel to the plane of the wall in the vicinity of an opening on the wall of building, this theory relate the characteristics of local flow at an opening with ventilation rate. This theory is excellent in respect of accounting for the wind direction (i.e. incident angle). Although there is a defect that this theory cannot be necessarily applied to the room with plural openings of various opening areas, this theory is very valuable for predicting the ventilation rate of a room with a single opening.

The aim of this study in this paper is to investigate the relation between the various factors of the local flow at the surface of building and the air flow rate of the room with a single opening under various conditions of factors, and to verify both the usefulness and the application limit of this theory.

EXPERIMENTAL METHOD

For the above-mensioned purpose, wind tunnel test is conducted. Figure 1 shows the section of the working section of wind tunnel. Used wind tunnel is closed jet type whose dimensions are 1.8*1.8 m in section. A cubical enclosure made of plywood (80*80*80cm) is attached to the side wall of wind tunnel and this enclosure has one wall in common with the side wall of the wind tunnel. The enclosure has a small fan to mix the air in it. The panels containing openings of various types can be inserted flush with the tunnel wall. The panel can be set with a certain angle between the stream direction and the longer side of the opening. The openings are square, circular and rectangular as listed in Table 2. The lattice of different size can be settled at the intake of working section of wind tunnel in order to change the turbulent characteristics of air flow in the wind tunnel.

The ventilation rate of the enclosure is measured by tracer-gas method. The ventilation rate is calculated by the equation by Seidel from the data of decaying gas concentration. CO_2 gas is used as tracer. Under various conditions of mean wind velocity and turbulent intensity of air flow inside the wind tunnel, the decrease of CO_2 cncentration inside the enclosure with each single opening is measured. As the air in the enclosure is continuously stirred up by fan, the computed ventilation rate can be considered to be equal to the air flow rate through the opening. As listed in Table 2, the varied parameters are mean wind velocity, turbulent intensity (scale of turbulence), shape of opening, area of opening and the angle θ between stream line and the longer side of rectangular opening. Tests are not conducted under the all combinations of these parameters, but a certain parameter is varied at the other parameters fixed. The mean wind velocity means the mean air velosity measured by non-directional anemometer at the point of 20 cm distance from the surface of wind tunnel wall.

RESULTS

Before the investigation into the effect of various factors, the characteristics of approaching air flow inside the wind tunnel have to be made clear. Figure 2 shows the profile of mean wind velocity and root mean square (R.M.S.) of fluctuating component of wind velocity at the mean velocity of 6 m/s. There is a little difference between these velocity profiles of different types of wind. The maximum difference of velocity at 1 cm distant from the wall surface is about 15 % of velocity. In each case of wind type, the closer to the wall the higher the R.M.S. of velocity fluctuation is. Fig. 3 show the profile of the scale of turbulence calculated by integrating auto-correlation function.(at V=6m/s) Though there is some scattering, the scale is different between the type of wind and the scale of wind type 3 is about 20-30 cm, 30-40 cm as for type 2, and 50-60 cm as for type 1. The scale of turbulence is a little larger than the length of some openings and as much as that of other openings.

The ventilation rate generated by the mixing fan in the case of the square opening under the windless condition is about 3.5 m^3/h, which is not negligible. Nevertheless, whether the mixing fan is used or not used, there is little difference among estimated ventilation rates when wind blows in the wind tunnel.

In the equation by P.R.Warren, the air flow rate through an opening is in proportion to the air velocity local to the opening, but the limit of application have to be made clear. The following examination is to verify the usefullness of this equation and the limit of application.

Fig. 4 shows the relationship between the mean air velocity at the point of 20cm distant from the wall and the air flow rate of the enclosure with various shapes of opening whose opening areas are the same.(at θ =90 deg. :angle of flow direction in plane parallel to wall) This shows that the air flow rate is not proportional to mean air velocity when the aspect ratio is 8 or 16 and θ is equal to 90 deg. On the other conditions of opening, the air flow rate is nearly in proportion to the mean air velocity. There is little differnce of air flow rate between openings at V = 3 m/s , but the greater the mean air velocity becomes the larger the difference of air flow rates is.

Fig. 5 shows the same relationship on the opening condition of aspect ratio 2. The relation between the mean air velocity and the air flow rate could be expressed by a convex curve open upwards except for two plots at θ =90 and V=9 m/s. But, when this relationship is assumed to be linear, there seems to be no serious problem so long as the mean air velocity is nearly in this range of 0 - 10 m/s for practical use. On the other hand, even if the mean air velocity is the same, the air flow rate shows 20 per cent gain at wind type 1. It can be considered to be caused by the effect of higher turbulent intensity near the wall. Fig.6 shows the same relationships as for the openings of different areas. (θ = 90, aspect ratio = 2) The similar tendency can be seen in this figure. As shown in Fig.5, the convex curve will be suitable to express this relationship, but if straight line is drawn, the variation of the plots from the line is rather small.

The relationship between the angle of flow direction in plane parallel to wall and the air flow rate for the wind type of 2 is shown in Figure 7. It is apparent that there is the largest differnce between the different shapes of opening at θ=90 degree, and the smallest at θ=45 . The thin opening like a slit get the largest air flow rate when air flows along the longer side of the opening. For the rectangular opening like a square, the relation between both can be expressed by a convex curve open upwards. The openings of aspect ratio 8 and 16 have such a different tendency that there remains the possibility that the air flow rate of these openings is linear to the mean air velocity as long as θ=0. Fig. 8 shows the relationship as for the rectangular opening of aspect ratio 2. It is clear that the difference of air flow rate caused by the angle of θ does not appear at V=3 m/s, but the higher the air velocity becomes, the larger the different does. This is very serious tendency because this means that there is no specifying the characteristics of opening as a function of the angle of wind direction, which is not independent of the mean air velocity. From this figure, it is shown that the difference of wind type come into view on the condition of V=9 m/s and θ =90 degree.

Lastly in the investigation, the relationship between the opening area and the air flow rate in the case of V=6 m/s and aspect ratio 2 are shown in Fig. 9. The air flow rate is in direct proportion to the opening area at least under the conditions listed in this figure. The equation by P.R.Warren is very applicable in respect of the effect of opening area, although there may be some limitation for adaptation.

CONCLUDING REMARKS

1)The air flow rate is not proportional to mean air velocity when the aspect ratio is 8 or 16 and θ is equal to 90 degree.
2)If the air flow rate is assumed to be in proportion to the mean air velocity local to the opening, there seems to be no serious problem so long as mean air velocity is nearly in the range of 0 - 10 m/s for practical use and the aspect ratio of opening is 2.
3)The thin opening like a slit get the largest air flow rate when air flows along the longer side of the opening; i.e.at θ = 0 degree.
4)There is no specifying the characteristics of openings as a function of the angle of wind direction θ , because it is not independent of the mean air velocity.
5)The air flow rate is in direct proportion to the opening area at least under the conditions listed in this paper.

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Table 1 The equation for the calculation of air flow rate by P.R.Warren

$$Q = \alpha A U_L g(\eta)$$

- α :arbitrary constant relating to the width of mixing layer
- A :area of opening
- U_L:mean velocity local to the opening
- $g(\eta)$:function of similarity variable

Table 2 The conditions of varied parameters

Parameter				
Mean wind velocity to be set V (m/s)		3	6	9
		(at the distance of 20cm from the wall)		
Type of wind		1	2	3
Turbulent intensity (%)		high	medium	low
Opening	shape	circle, rectangle (1, 2, 8, 16 of aspect ratio)		
	area (cm²)	225		
	shape	rectangule of aspect ratio : 2		θ
	area (cm²)	225, 450, 675		
Angle of flow direction in plane parallel to wal θ (degree)		0, 22.5, 45, 67.5, 90		wind / opening

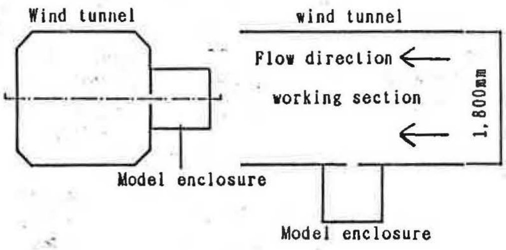

Figure 1 Section of wind tunnel

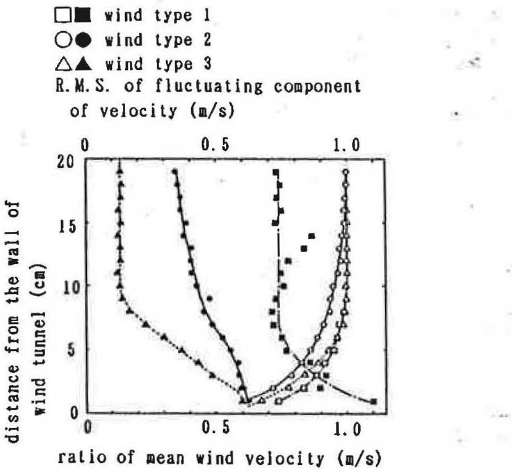

Figure 2 The profile of mean wind velocity and root mean square of fluctuating component of wind velocity (V=6 m/s)

○△□ mean velocity ●▲■ R.M.S.

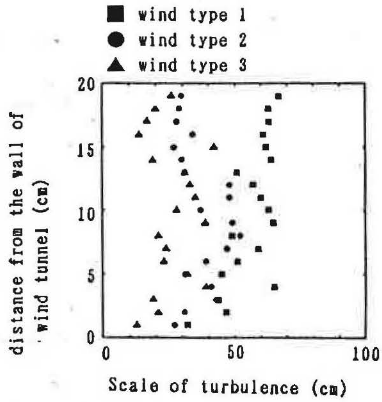

Figure 3 The profile of the scale of turbulence (V=6 m/s)

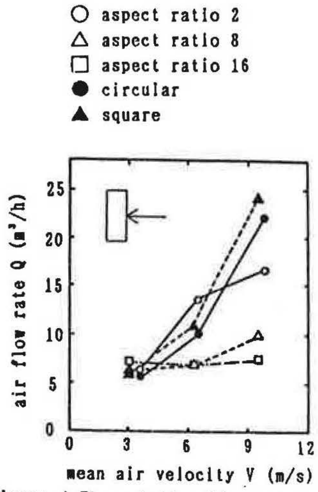

Figure 4 The relationship between the mean air velocity at the distance of 20cm and the air flow rate Q (θ =90, wind type 2)

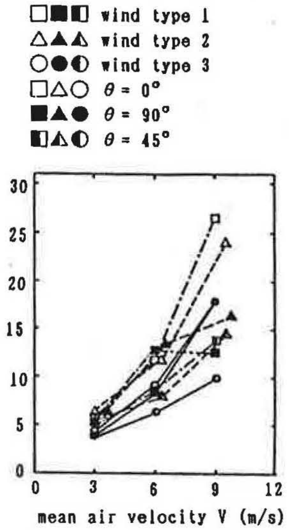

Figure 5 The relationship between the mean air velocity and the air flow rate Q (aspect ratio = 2, openig area 225cm²)

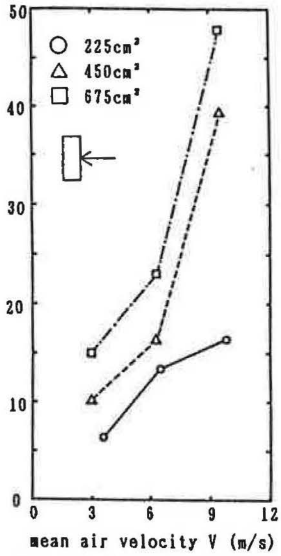

Figure 6 The relationship between the mean air velocity and the air flow rate Q (θ =90, aspect ratio=2)

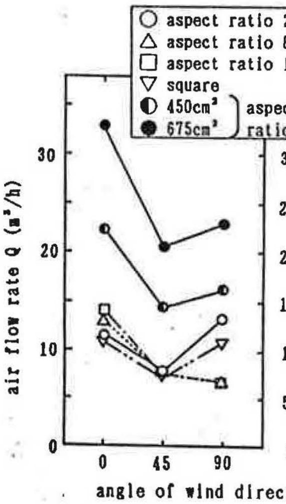

Figure 7 The relationship between the angle of flow direction θ and the air flow rate Q (wind type 2)

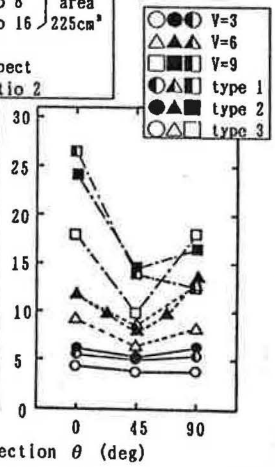

Figure 8 The relationship between the angle of flow direction θ and the air flow rate Q (aspect ratio 2)

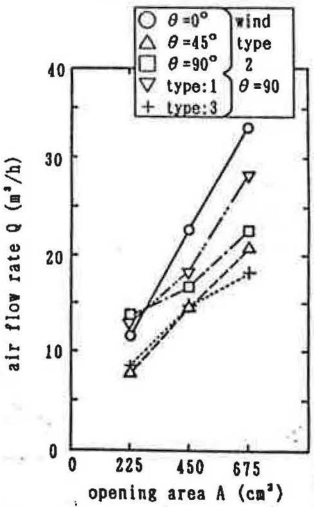

Figure 9 The relationship between the opening area A and the air flow rate Q (V=6 m/s, aspect ratio 2)