Power Transportation Analysis inside Stream Tube of Cross-Ventilated Building

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ABSTRACT

In predicting flow rate of a cross-ventilated building, discharge coefficients obtained from the connected value of resistance coefficient of opening based on the chamber method, and the wind pressure coefficients from a sealed building are usually used. This method can predict the flow rate well for the case of small openings. For the large openings, however, it is well known that flow rate could be underestimated because these are not based on actual condition. Authors aim to establish the prediction method of flow rate based on "power balance" inside the stream tube flowing through/around a building. In order to predict flow rate by this method, transported powers on specific sections and those losses between the sections need to be known finally. In this paper, therefore, the stream tube caught by the opening is determined by using CFD for the simple shaped rectangular models as the first step of analysis. Finally, the transported power and power losses are to be investigated.

1. INTRODUCTION

From the viewpoint of saving energy, utilization of natural energy has been an interest of many researchers and designers of buildings. Wind-induced natural ventilation has been an effective method to obtain thermal comfort in hot summertime in Japan. In predicting flow rate of a building ventilated by wind, following equation based on Bernoulli's principle is generally used.

$$Q = C_D A_{Opening} \sqrt{\frac{2}{\rho}(P_W - P_L)} \qquad (1)$$

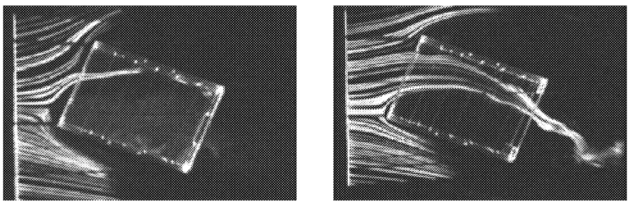
where :

C_D : Discharge coefficient obtained from the chamber method conducted under the windless condition by using a fan [-].

P_W : Wind pressure on the windward wall where opening is to be provided [Pa].

P_L : Wind pressure on the leeward wall where opening is to be provided [Pa].

It is well known that the flow rate predicted by this method could be accurate for the case of small openings like cracks, because flow is diffused enough after passing through an opening and its kinetic energy is almost dissipates as it is in the chamber method. On the other hand, if the openings are large, kinetic energy is preserved inside a room and even after flowing out as shown in Figure 1 (Kotani and Yamanaka (2006)) and for this case, the flow rate predicted based on the conventional method could be underestimated. In addition, It is also questionable to use wind pressure coefficient obtained from a sealed building for the prediction of porous building.



a) Small openings b) Large openings

Figure 1. Difference in flow through openings

Kobayashi et al. (2007) have shown these problems on flow rate by analyzing the stream tube flowing through the cross-ventilated objects by using CFD. Ishihara (1969) illustrated this problem as *Interference* between openings and modified the discharge coefficient by using interference factor. Kurabuchi et al. (2002) introduced *Local Dynamic Similarity Model* by using dimensionless internal pressure that indicates the ratio of driving force to disturbing force. Sandberg (2002) has shown the geometrical parameter of *Catchment Area* and investigated the relation to the porosity (opening area divided by façade area).

Murakami and Kato et al. (1991, and 2004) proposed that flow rate be predicted based on energy balance inside stream tube (power balance model), and derived the equation of lost power, as this idea was originally introduced by Guffy et al. (1989). Recently Axley (2005) introduced almost the same theory based on mechanical energy balance. These models seem to be appropriate to predict flow rate of a building provided with large openings where kinetic energy is preserved because these are based on actual condition under the wind. The major problem to utilize power balance model is how to evaluate transported power on specific cross section of the stream tube and the power loss between them. Authors aim to establish new prediction method based on power balance, which is appropriate even for the case of large openings. In this paper, therefore, the stream tube caught by the opening is determined by using CFD. Then transportation of the power inside the stream tube is to be investigated.

2. METHOD

2.1 Model and Cases

Based on the previous wind tunnel test (Kobayashi et al, 2006), the rectangular model shown in Figure 2 was used for the analyses. For the parametric analysis, side length of the openings (L) and model depth (D) were changed as shown in Figure 3. For all cases, models have the side walls whose thickness is 6.0 mm. As for the end walls, 0.8 mm thick wall was provided in order to obtain sharp edges.

2.2 Summary of CFD

Figure 4 shows computational domain in CFD simulating the wind tunnel test. Meshed area indicates the domain assuming vertical and horizontal symmetry to reduce the calculation load. Table 1 gives the details of the number of grids in Figure 4. Fluent 6.2 was used for the analysis.

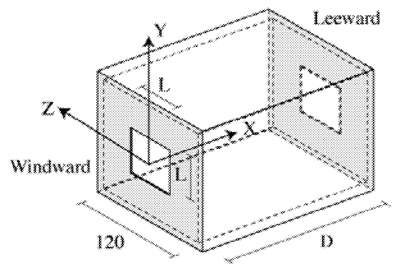


Figure 2. Geometry of Studied Model (unit is mm)

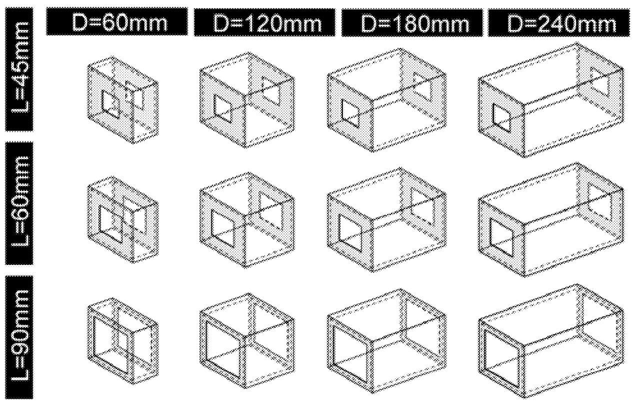
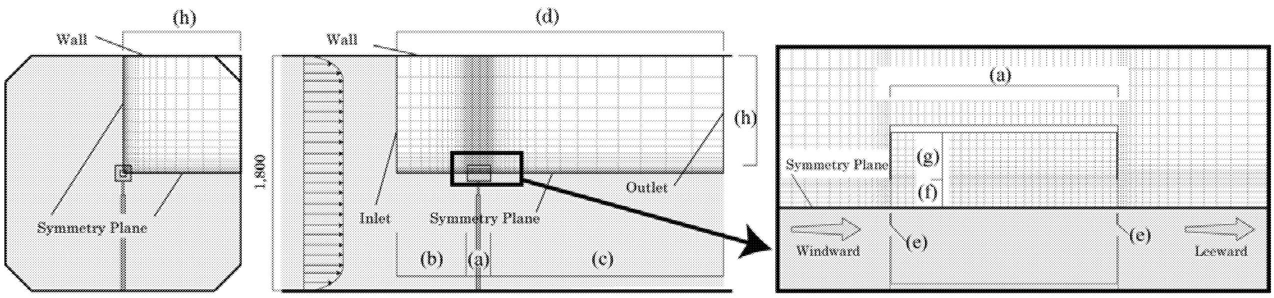


Figure 3. Studied cases for CFD analysis



(1) Y-Z Section (2) X-Z Section (3) Detail of X-Z Section

Figure 4. Computational Domain for CFD Analysis

Table 1. Number of grids shown in Figure 4

		(a)	(b)	(c)	(d)	(e)
D = 60 mm	Length [mm]	60	500	1,500	2,061.6	0.8
	Number of grids	20	28	40	88	4
D = 120 mm	Length [mm]	120	500	1,500	2,121.6	0.8
	Number of grids	40	28	40	108	4
D = 180 mm	Length [mm]	180	500	1,500	2,181.6	0.8
	Number of grids	58	28	40	126	4
D = 240 mm	Length [mm]	240	700	2,000	2,941.6	0.8
	Number of grids	80	32	44	156	4

		(f)	(g)	(h)
L=45 mm	Length [mm]	180	500	1500
	Number of grids	50	28	40
L=60 mm	Length [mm]	180	500	1500
	Number of grids	50	28	40
L=90 mm	Length [mm]	180	500	1500
	Number of grids	50	28	40

Table 2. Summary of CFD Analysis

CFD Code	FLUENT 6.2	
Discretization Scheme for advection term	QUICK	
Algorithm	Steady state (SIMPLEC)	
Boundary condition	Inlet	Velocity : 10 m/s Turbulent Intensity : 1% Turbulent Length Scale : 126mm
	Outlet	Gauge Pressure : 0 [Pa]
	Walls	Wall : no slip Symmetry : free slip
Turbulence model	Reynolds stress model (RSM)	

Table 3. Total number of meshes

	L = 45	L = 60	L = 90
D = 60	1,069,408	1,073,512	1,078,912
D = 120	1,288,408	1,315,512	1,320,912
D = 180	1,526,904	1,503,264	1,502,337
D = 240	1,846,208	1,896,312	1,901,712

SIMPLEC pressure-velocity coupling algorithm was used with quick discretization scheme for the advection term. As for the turbulence model, Reynolds Stress Model was used based on previous accuracy study shown in Kobayashi et al. (2006). Table 2 summarizes the setting of CFD analysis and Table 3 shows the numbers of grids for all the cases.

2.3 Boundary Conditions

As the inlet boundary condition, free flow of 10 m/s was given with its turbulence intensity 1.0 % and 126 mm of turbulence length scale (0.07 times of hydraulic diameter of the wind tunnel cross section). As for the outlet boundary condition, gauge pressure was fixed as 0 Pa.

3. DETERMINATION OF STREAM TUBE

Based on calculated results, the stream tube passing through the model was determined by setting out particles from the edge of the inlet opening. As for the leeward side of the model, particles were set out from that of the outlet opening. However, some particles circulating or flowing to negative direction behind the model were seen, especially in the case of small openings and small depth. In those cases, therefore, points to set out particles were moved toward the center of the opening until set out particles flowed into only positive direction as shown in Figure 5.

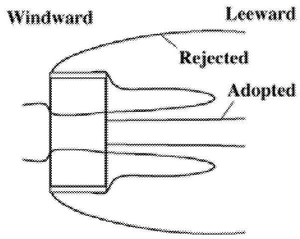


Figure 5. Rejection and adoption of the particles on the leeward side of model

4. RESULTS AND DISCUSSIONS

4.1 Cross Sectional Area

As the first analysis of the stream tube, the cross sectional area was calculated based on the outline composed of particles by integrating trapezoids as shown in Figure 6, which indicates a quarter of the cross section. Figure 7 shows the results of the cross sectional area, where vertical axis is dimensionless area divided by opening area and horizontal axis indicates the distance from the inlet opening divided by model length. Shaded area indicates the model. On far upstream side of the model, difference in cross sectional area indicates that in flow rate because of the free flow. In the case of large depth, this becomes small due to large resistance of the model. The opening size is also an important factor to determine the shape of the stream tube. In the case of small openings, relative change in shape becomes large because of collision to the end walls. It can be easily imagined that stream tube becomes like a pipe for the extremely large openings. In the case of small depth and small openings, sudden contraction of the stream tube can be

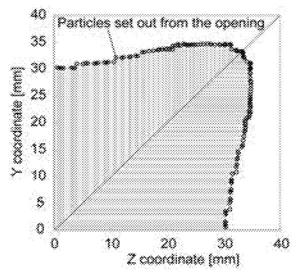


Figure 6. A quarter of determined cross section

seen at the outlet opening. This is due to the discontinuity of the stream tube illustrated in Figure 5. Although this can be a problem in determining the stream tube, it will be discussed and modified in following section 4.4.

4.2 Average Pressure inside Stream Tube

Figure 8 shows the flow rate weighted-average total pressure inside the stream tube, which is divided by the total pressure of far upstream cross section. In all cases, total pressure is almost constant on the windward side of the model. After flowing into the model, as a common tendency, total pressure starts to decrease, and on the leeward side, total pressure recovery can be seen because of energy supply from the external stream tube passing around the model. In the case of large openings, total pressure loss naturally becomes small. However, model depth is also important. Total pressure loss becomes larger inside the model in the long model case. As for the leeward side, larger loss can be seen in the case of short models. As a result, minimum total pressure becomes smaller in the case of small depth. Here, as for the cases of short length and small opening, total pressure increases at the outlet opening. This is also due to discontinuity of the stream tube. The rationale is that the perimeter area of the stream tube, where total pressure is low, is omitted in the procedure of determination. In order to evaluate energy loss adequately, therefore, it

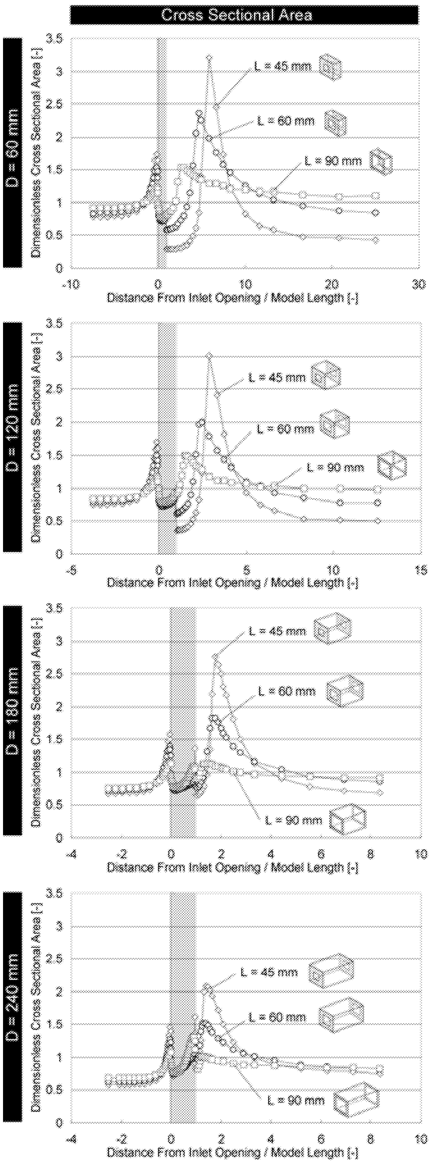


Figure 7. Cross sectional area of determined stream tube

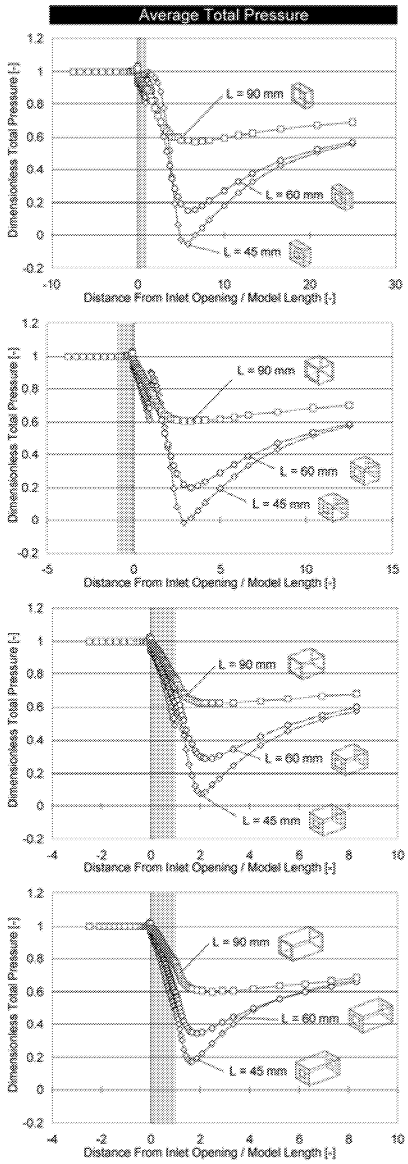


Figure 8. Average total pressure inside stream tube

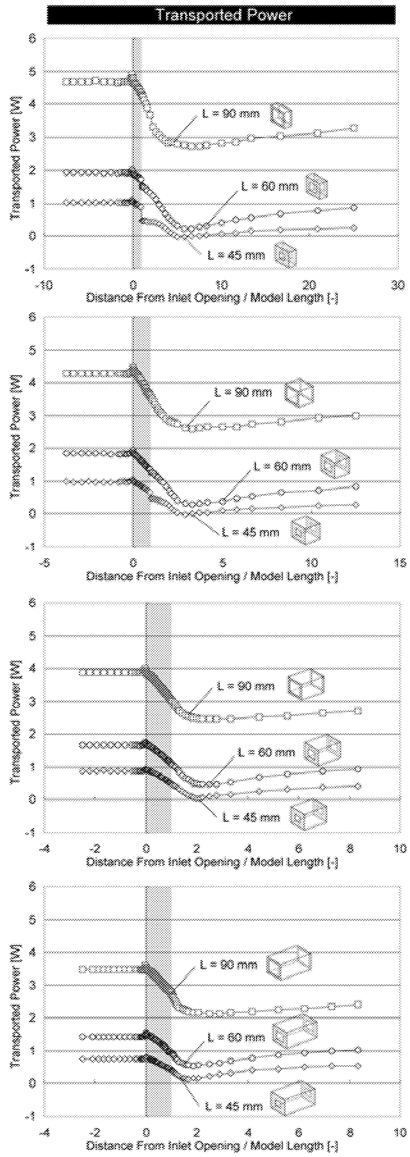


Figure 9. Transported power inside stream tube

seems appropriate to calculate the net power transported inside the stream tube.

4.3 Transported Power and Lost Power

In order to know the basic mechanism of energy flow, transported power [W] inside stream tube is calculated by multiplying flow rate weighted-average total pressure [Pa] by the flow rate [m^3/s] on each section as Murakami et al. (1991) and Kato (2004) showed. Figure 9 shows the results. To apply the power balance model into the practical prediction, these powers on specific sections of the stream tube and lost power between them are to be known. Differences in the power on the windward side among all the cases result from those in flow rate because of the uniform total pressure. In Figure 10, decrease of the power from the windward section is shown as lost power. Comparing the case of large openings with that of small openings, transported power on the windward side is approximately four times. However, the maximum value of the lost power is two times. As for the case of L=45mm, D=60mm, at the outlet opening, discontinuity of the stream tube causes sudden change in power, and also in lost power consequently. As it was mentioned above, some more investigations on the power of omitted area of the stream tube are to be shown in following section.

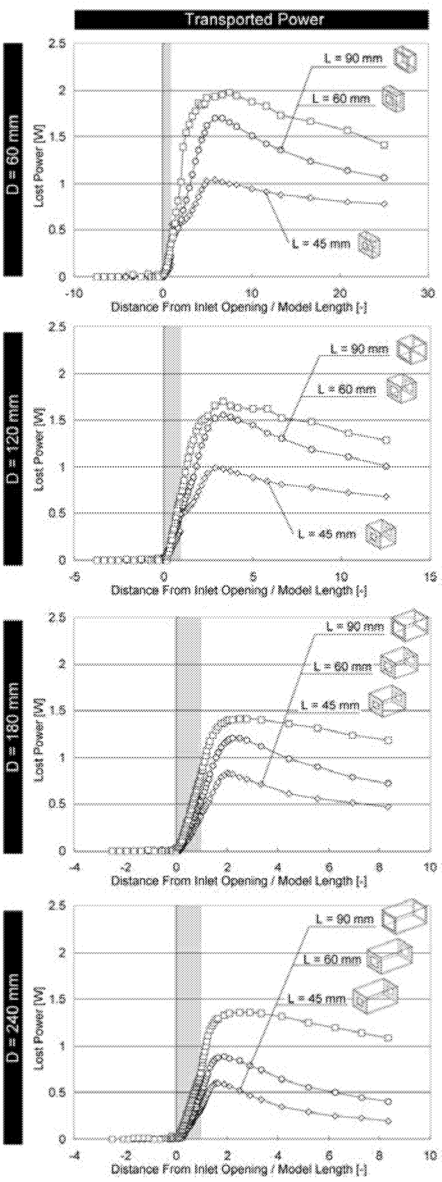


Figure 10. Lost power inside stream tube

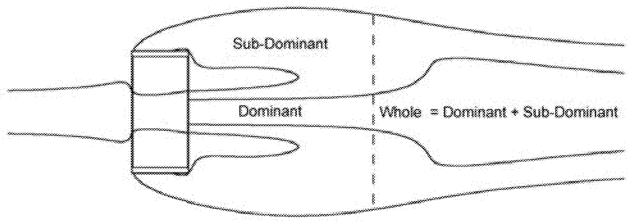
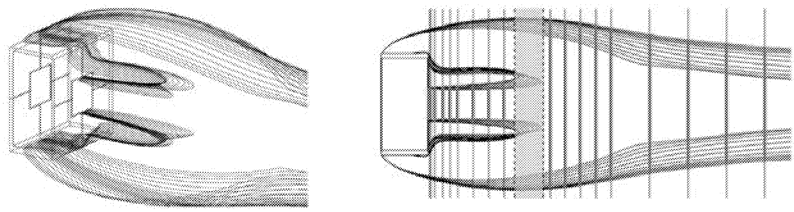
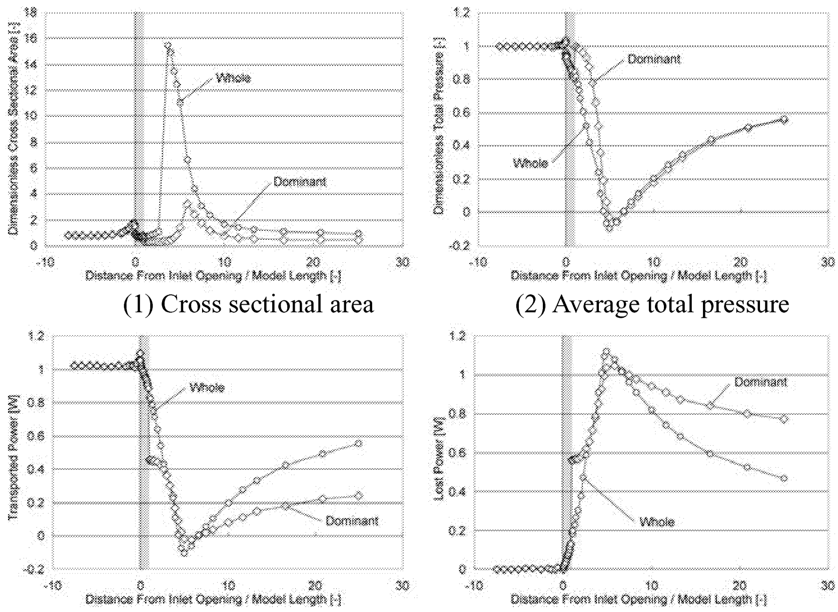


Figure 11. Definition of dominant and whole stream tube


(1) Perspective view

(2) Projection (Stream tube was not determined in shaded area)

Figure 12. Method to determine whole stream tube



(1) Cross sectional area

(2) Average total pressure

(3) Transported power

(4) Lost power

Figure 13. Comparison between whole and dominant stream tube

4.5 Modification for Leeward Stream Tube

In the case of L=45mm, D=60mm, the stream tube determined on the leeward side was only a part flowing to downward directly as shown in Figure 5. Here, we define this part as *dominant stream tube*, the other part flowing negative direction as *sub-dominant stream tube*, and also *whole stream tube* altogether (See Figure 11). In order to evaluate the power transportation adequately, it seems appropriate to determine whole stream tube. Figure 12 (1) shows a part of particles composing the whole stream tube. It was determined except the shaded area shown in Figure 12 (2) where some particles flow positively, and others, negatively. Although this stream tube flows backward once, it can be regarded as continued stream tube from the windward part. The whole stream tube is compared with the dominant stream tube in Figure 13. As for the cross sectional area, extreme enlargement can be seen on the leeward side. Of course this occurs across the shaded area in Figure 12 (2). Total pressure recovery at the outlet opening cannot be seen in the whole stream tube. As for the transported power and power loss, smooth decrease/increase is shown at the outlet opening. Here it must be noted that minimum value of transported power of the whole stream tube and the dominant stream tube results in almost the same. It means that the power owned by sub-dominant stream tube at the outlet opening has almost been dissipated. Then, power is supplied from the outer stream tube passing around the model to the sub-dominant stream tube first, and after that, a part of the power is transported into the dominant stream tube as shown in Figure 14.

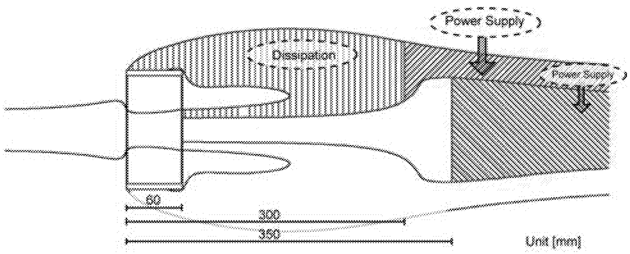


Figure 14. Power transportation from outer stream tube

In order to apply the power balance model, transported power and lost power need be known also within the external stream tube. Therefore, the external stream tube is also to be investigated as a future prospect.

5. CONCLUSIONS

- In cross-ventilation phenomena, conventional method can underestimate the flow rate.
- With the purpose of establishing prediction method based on power balance, transported power inside stream tube was calculated.
- For the case of small openings and small depth, the dominant stream tube and the whole stream tube were defined and basic energy flow was shown.
- As a future prospect, the external stream tube also need to be investigated.

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