STUDY ON AIRFLOW CHARACTERISTICS IN AND AROUND BUILDING INDUCED BY CROSS VENTILATION USING WIND TUNNEL EXPERIMENT AND CFD SIMULATION

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ABSTRACT

In the present study, airflow characteristics were evaluated in and around 5 types of building models induced by cross ventilation in case opening conditions and approaching flow angles were different. Both techniques of wind tunnel experiment and numerical simulation were employed, and the problems and advantages of these methods were discussed. The airflow characteristics were discussed from the following 4 viewpoints: wind pressure coefficient distribution, air velocity distribution, ventilation rate, and main airflow path. As a result, it was found as follows: 1) When opening was positioned approximately at the center of windward or leeward walls and approaching flow angle was 0°, the difference of wind pressure coefficients on the walls was within 0.2 even when the opening conditions were different. Thus, overall flow around the building was not changed within the range of the opening conditions under the present study, and the airflow passing through the windward opening ran downward. 2) In case approaching flow angle was different, wind pressure coefficient was decreased with the increase of the approaching flow angle. The airflow passing along wall surface was changed in transverse direction. Air velocity was also increased, and ventilation rate was decreased. When the approaching flow angle exceeded 45°, flow resistance at the windward opening increased. In case the airflow entered without running perpendicularly to windward wall, the airflow ran straight after entering the windward opening.

KEY WORDS

Cross ventilation, wind tunnel experiment, CFD, approaching flow angles, opening conditions

1. INTRODUCTION

Cross ventilation is currently being reconsidered from the viewpoint of energy saving. The airflow characteristics induced by cross ventilation, factors such as opening conditions (including opening area, position of opening and number of openings), partitions, wind pressure and ventilation rate due to difference in approaching flow angle, airflow characteristics, and energy balance were evaluated in the studies published using wind tunnel experiment and numerical simulation. Wind tunnel experiment requires much time and labor, and above all, it is difficult to perform static pressure measurement or total pressure measurement in a space where airflow direction cannot be identified. Numerical simulation has also problems such as the problems of turbulence model, numerical error associated with finite difference scheme or insufficient resolution of mesh layout. However, it is possible by numerical simulation to calculate total pressure, static pressure and dynamic pressure at any points, and it has advantages in that effective supplementary information can be obtained a quantity, which cannot be determined by wind tunnel experiment.

In this respect, we attempted in the present study to discuss estimation of airflow characteristics in and around a building induced by cross ventilation using the results of wind tunnel experiment and numerical simulation when opening conditions and approaching flow angles are different. The discussion will be developed from 4 viewpoints, i.e. wind pressure coefficient distribution, air velocity distribution, ventilation rate, and main airflow path.

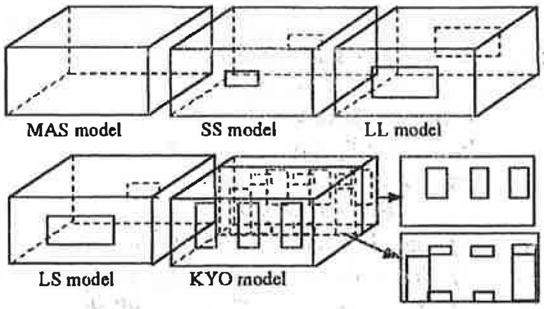

Figure 1 Models

Table 1 Openings on windward wall and leeward wall and the number of measuring points of each model

Model	Windward wall	Leeward wall	Number of measuring points
SS	S opening	S opening	143
LS	L opening	S opening	123
LL	L opening	L opening	111
MAS	No opening		65
KYO	Classroom,	Partitions	146

※S opening : 0.2Hb × 0.4Hb, Percentage of opening area:4%
※L opening : 0.4Hb × 0.8Hb, Percentage of opening area: 16%

Table 2 Models and approaching airflow angles of each measurement

	MAS	SS	LL	LS	KYO
0°	○	○△□◇	○△□◇	○△□◇	○△□◇
22.5°	○	○△	–	–	○△
45°	○	○△□	□	–	○△
67.5°	○	○	–	–	○
90°	○	–	–	–	○

○:Wind pressure coefficient △:Ventilation rate at the leeward opening □:Distribution of air velocity ◇:Visualization experiment

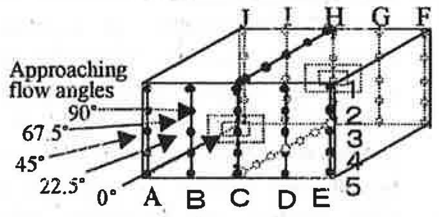

Figure 2 Approaching flow angles and location of measuring points

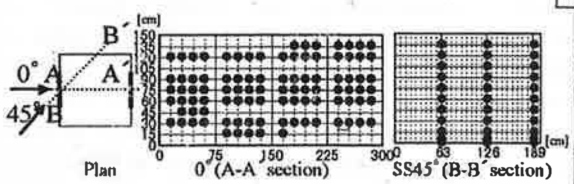

Figure 3 Measuring points of air velocity in SS model at the approaching flow angle of 0° and 45°

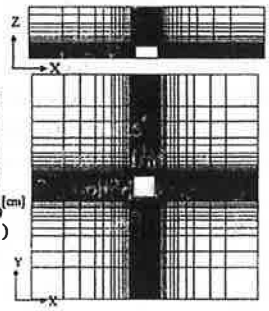

Figure 4 Mesh layout

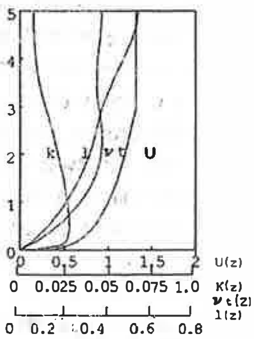

Figure 5 Vertical Distribution of variables

2. METHODS

2-1 Outline of Wind Tunnel Experiment

In the present study, the following 4 types of experiments were performed: (1) measurement of wind pressure on wall surface; (2) measurement of ventilation rate at leeward opening; (3) measurement of air velocity distribution in models to determine main airflow path; and (4) visualization experiment.

The experiment was performed using Eiffel type boundary layer wind tunnel at Faculty of Engineering, Tokyo Institute of Polytechnics. Approaching flow was set to air velocity distribution in accordance with 1/4 power law profile. For measurement of air velocity, a thermistor type anemometer was used.

In the present study, 5 types of building models having the same outline dimensions as shown in Figure 1 were prepared. Each model has different opening condition such as presence of opening or opening area because these factors may give extensive influence or the airflow characteristics in and around the building. The model was prepared in form of a rectangular parallelepiped of 1:2:2 with the height of the model ("Hb"; 15 cm in real size) as reference. Wall thickness was set to 1/20 Hb. MAS model is a model without opening for the purpose of identifying wind pressure on wall surfaces. SS model or LL model shown in Table 1 are the models, each having 2 types of openings such as S opening (0.2 Hb x 0.4 Hb) or L opening (0.4 Hb x 0.8 Hb) on windward and leeward walls at the center of wall surface. LS model has L opening on windward wall and S opening on leeward wall. These models are identical with the building models used in numerical simulation by Kurabuchi et al.[2] Further, KYO model was added, which simulates classroom and corridor. Because openings in school classroom and corridor are windows or doors of double sliding type in most cases, it was assumed that one-half of the window area on the same side is opened in each case.

Positions of the measuring points, names of columns of the measuring points, and number of rows of the measuring points, and approaching flow angles at the time of measurement in these models are shown in Figure 2. There were 5 measuring points in each of 4 columns on internal and external walls of windward and leeward walls, more than 5 points in the column of the central axis, 7 points on the central axis on rooftop, 5 points on the central axis on each of ceiling and floor surface, and several points near each opening. Wind pressure coefficient on lateral side was not given because it correspondes to the wind pressure coefficient on windward and leeward walls when approaching flow angles was changed. Table 2 shows building models used in each of the four types of experiments.

2-2 Experimental Method

a. Measurement of wind pressure on wall surface

Pitot tube static pressure outside the boundary layer was used as reference pressure, and standard dynamic pressure was calculated from air velocity of the approaching wind at the height of the model. Re number at the height of the model was set to about 67,000. Micro differential pressure gauge was used for measurement of wind pressure. In the measurement of wall surface wind pressure, it was assumed that approaching flow angle was 0° in case main direction of airflow is at right angle to the opening of the building model, and the angle between angle of 0° and main direction of airflow was considered as the approaching flow angle. To identify the difference of wind pressure coefficients caused by the difference of the opening conditions, MAS, SS, LL, and LS models were used. To assess the change of wind pressure coefficient at every 22.5° for the approaching flow angle of 0° to 90°, MAS, SS, and KYO models were used.

b. Measurement of ventilation rate

Ventilation rate was measured at the leeward opening. The leeward opening was hypothetically divided to squares each being 1 cm x 1 cm for S opening and L opening, and to rectangles each being 0.9 cm x 0.75 cm for KYO opening. Mean air velocity at the center of these divided areas was measured by installing a thermistor type anemometer immediately near the leeward opening. Mean air velocity at the opening was obtained, and ventilation rate was calculated from the product of mean air velocity and opening area. The number of air velocity measuring points was: 18 points for S opening (SS and LS models), 72 points for L opening (LL model), and 150 points for KYO opening.

c. Main airflow path inside the building

To identify main airflow path, scalar air velocity distribution in the model was measured using LL model and SS model, which have the same opening area on windward and leeward walls. Two types of approaching flow angles were used, i.e. 0° and 45°. Heated body type anemometer, in which directivity can be neglected almost completely, was inserted through a hole on the rooftop of the model, and time average air velocity was measured at every 1.5 cm in height direction and ventilation direction. Figure 3 shows positions of the measuring points. The number of measuring points was: 113 points when approaching flow angle was 0°, and 30 points when it was 45°.

d. Visualization experiment

Using all of the models, three wires wound in spiral form were immediately placed in front of the windward opening, and it was attempted to be visualized by liquid paraffin mist method: Liquid paraffin was passed incessantly, and by indreasing voltage at every 5 seconds using Sliduck, smoke was generated and it was photographed by stroboscopic method.

2-3 Outline of Numerical Simulation

Numerical simulation was performed on the same model as in the wind tunnel experiment including wall thickness. Mesh layout used was 80(x)×80(y)×39(z) as shown in Figure 4 for the whole, and 40(x)×40(y)×20(z) meshes are used for reproduction of the model. Calculation was performed for the whole area in MAS model

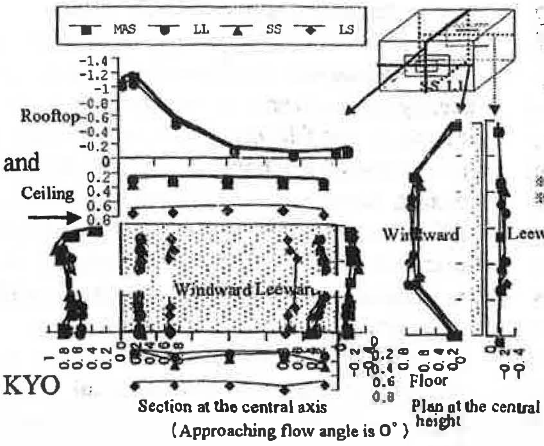

Figure 6 Measured wind pressure coefficients of each wall surface of models at the 0

Table 3 ventilation rate and pressure loss coefficients

model flow angles	SS 0°	SS 22.5°	SS 45°	LS 0°	LL 0°	KYO 0°	KYO 22.5°	KYO 45°
experiment	0.0459	0.0448	0.0419	0.0645	0.1978	0.3046	0.2905	0.2198
numerical simulation	0.0398 (87%)	0.368 (82%)	0.0274 (65%)	0.0584 (91%)	0.1912 (99%)	0.2497 (82%)	0.2320 (80%)	0.1779 (81%)
Pressure loss coefficient	1.32	1.45	1.78	1.26	1.21	—	—	—

※ Ventilation rate are standardized by air velocity and length at the height of a model
※ The numbers in the brackets are percentage of wind pressure coefficients measured by wind tunnel experiment against that conducted by numerical simulation

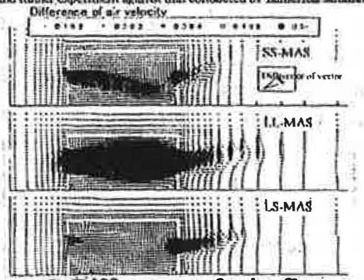

Figure 7 Difference of air flow around models between MAS model and other models

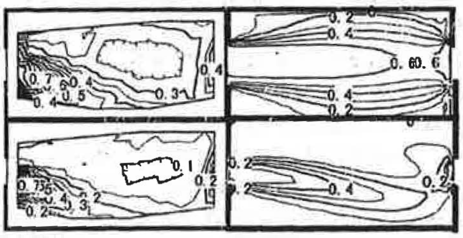

Figure 8 Measured and calculated air velocity distribution

model and in SS model with approaching flow angle of 22.5 to 90°. By taking symmetry into account, it was set to half-area for LL model, LS model and SS model with the approaching flow angle of 0°.

Figure 5 shows inflow boundary condition. This was obtained by numerically solving the κ-ε transport equation, assuming that airflow velocity is assumed and that differential other than vertical direction sets to 0. Upper, lateral and outflow boundary conditions of the calculation area were set to pressure type boundary condition. Wall surface, ground surface and floor surface were processed by wall function based on the assumption of 1/4 power law. Standard k-ε turbulence model was used as turbulence model. In a flow such as cross ventilation where energy balance is an important factor, finite difference approximation of convection term gives extensive influence on the results of numerical simulation. If artificial viscosity is too high, the balance between loss of mean flow energy and production of turbulence energy is not met, and it is not possible to numerically reproduce the mechanism to transmit the energy originally possessed by the turbulence model. In the present study, QUICK scheme is used, in which time and spatial oscillation of numerical solution is suppressed while false diffusion is expected minimal. To stabilize QUICK by full implicit method, coefficient of matrix was made identical with first order upwind scheme. Remainder components are corrected as source terms according to Hayase et al. Further, for convection and diffusion terms in the k and ε transport equation, PLDS (power method) was applied to avoid solution to become negative, and. For the other difference schemes, centered difference was adopted.

3. RESULTS AND DISSCUTION

3-1 Difference of Airflow Characteristics in and around the Building having Different Opening Conditions

3-1-1 Wind Pressure Coefficient Distribution in the Building having Different Opening Conditions and Mean Air Velocity Distribution in and around Building

Figure 6 shows wind pressure coefficients on vertical cross-section along the central axis of each of SS, LS, LL models having different opening areas and MAS model in case approaching flow angle is 0° where normal direction of the opening agrees with approaching flow angle. Opening area ratio of windward wall is 4% in SS model and 16% in LS and LL models. Difference of wind pressure coefficient between the models on each wall is within 0.2. Wind pressure coefficient on windward wall of LL model is by 0.18 lower than that of the other models, and formation of horse-shoe vortex is not observed. This may be because the opening area is large and a large quantity of air enters through the opening and force of the airflow is relatively reduced near the opening.

On the other hand, in the wind pressure coefficient of internal wall of each model, wind pressure coefficients are generally uniform on internal walls. In case of LS model, wind pressure coefficient is around 0.7, and this is by 0.3 to 0.5 higher than the value of 0.2 to 0.4 in the other models. This may be attributable to the fact that the wind pressure becomes closer to the wind pressure on windward side because flow resistance at the windward opening is low.

Figure 7 shows the differences of velocity vectors and absolute value of velocity between MAS model and other models. Airflow is changed near windward and leeward openings from the aspect of flow structure. But there is no substantial difference in overall flow, and wind pressure coefficient exhibits no extensive change.

3-1-2 Ventilation Rate in Buildings having Different Opening Conditions

When ventilation rates of the models in case approaching flow angle is 0° are compared in Table 3, ventilation rate is higher in the order of LL, LS and SS models. If SS model is taken as reference, ventilation rate of LL model, which has windward and leeward opening areas 4 times larger than that of SS model, and ventilation rate of LS model, which has equal opening area of the leeward wall, are 4.2 times and 1.4 times higher respectively. Further, Table 3 shows pressure loss coefficient, which was obtained by the conventional ventilation rate calculation method using wind pressure coefficient and ventilation rate measured by experiment. Naturally, the higher the ventilation rate is, the more the pressure loss coefficient is reduced.

3-1-3 Main Airflow Path in Buildings having Different Opening Conditions

In the results of measurement of air velocity in the models shown in Figure 8, flow entering at the windward opening is rapidly decelerated and falls down in case of SS model after it passes through the windward opening. In contrast, in case of LL model, the flow is gradually decelerated and deflected. Mean air velocity in LL model is by 0.15 m/s higher than that of SS model. The flow is accelerated again at the leeward opening and flows out.

3-2 Airflow Characteristics in and around Building when Approaching Flow Angles are Different

3-2-1 Wind Pressure Coefficient Distribution and Mean Air Velocity Distribution on Each Wall at Each Approaching Flow Angle

In case the approaching flow angle is changed by every 22.5°, wind pressure coefficient distribution on vertical cross-section along the central axis is not substantially different between MAS model and SS model, except that wind pressure coefficient of SS model is somewhat lower on the upper portion of the opening. Figure 9 shows vertical cross-section along the central axis and horizontal cross-section at the central height on the windward wall among the wind pressure coefficient distribution of SS model. The smaller the approaching flow angle is, the more the wind pressure coefficient on internal and external walls, ceiling and floor of the windward wall is increased. The reason for this may be as follows: As it is evident from approaching flow angles and air velocity of the airflow closer to the windward lateral wall in each approaching flow angles of SS model shown in Figure 10, when the approaching flow angle is increased, the central point where the stagnation point is moved toward the upper portion of the opening when approaching flow angle is 0° and toward left when it is 22.5°. The diverged flow runs diagonally along the wall surface when approaching flow angle is 22.5°, while it is deviated in lateral direction when approaching flow angle is 45° or more. Mean air velocity is also increased with the increase of approaching flow angle. In particular, when approaching flow

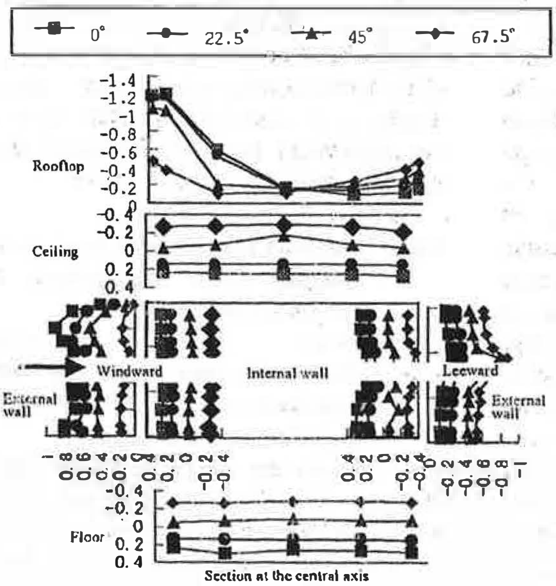

Figure 9 Distribution of wind pressure coefficient on each external and internal wall at the central axis

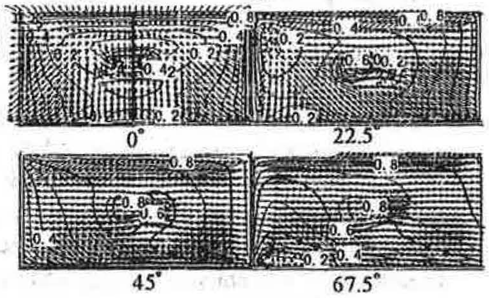

Figure 10 Calculated velocity vectors on the wind ward wall at each approaching flow angle

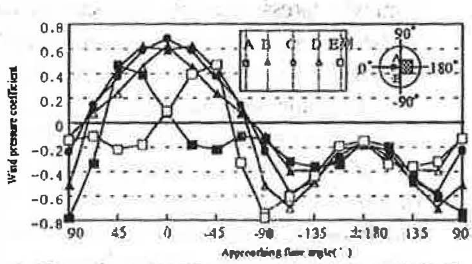

Figure11 Change of mean wind pressure coefficient of each column in every 22.5

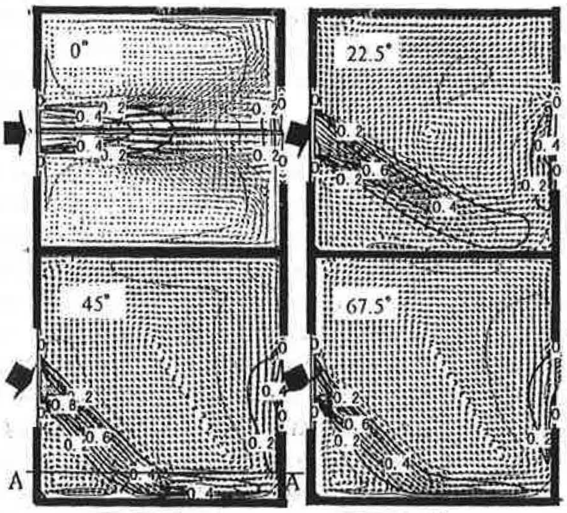

Figure 12 Calculated velocity vectors plan at the central height of SS model at approaching flow angle in every 22.5°

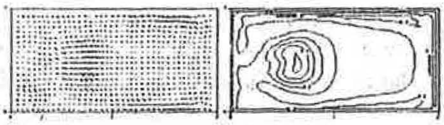

Figure 13 Calculated velocity vectors and contours section on A-A axis at the approaching flow angle of 45 using SS model

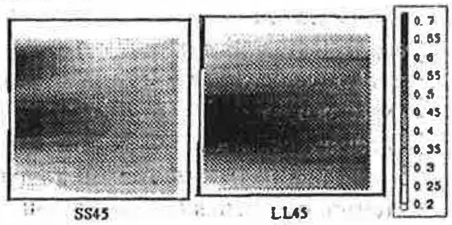

Figure 14 Distribution of velocity contour in SS and LL models at the approaching flow angle of 45

angle is 67.5°, rapid acceleration occurs at left end, and it is 0.8 around the windward opening. Figure 11 shows the change of mean wind pressure coefficient in the column of each measuring point due to approaching flow angles. Mean wind pressure coefficients of the columns of the measuring points are all positive when approaching flow angle is 0°, while mean wind pressure coefficient of column A is turned to negative pressure when approaching flow angle is –22.5° and –45°. When it is –67.5°, the coefficient is turned to negative pressure at columns A and B. Mean wind pressure coefficients of columns of all measuring points between –90° and 90° are turned to negative pressure. The closer the approaching flow angle is changed to –180°, the smaller the difference of mean wind pressure coefficient between columns of the measuring points is, and variation is decreased.

On the other hand, wind pressure coefficients in all approaching flow angles on the leeward walls are all in negative pressure, and there is not much difference due to the positions. The more the approaching flow angle is increased, the smaller the absolute value of negative pressure on the central axis becomes. However, conical vortex is actually formed, and it is estimated that higher negative pressure occurs at the corners. At the columns A and E, the wind pressure coefficient of the column on the leeward side when the approaching flow angle is 22.5° is turned to negative pressure. As shown in Figure 10, this is not because airflow is separated but because static pressure is decreased due to increase of dynamic pressure. When the approaching flow angle is 0°, negative pressure is also observed partially in both wind tunnel experiment and CFD at both ends of the windward wall due to the same phenomenon.

Further, in the internal pressure, wind pressure coefficients are uniform, and the more the approaching flow angle is increased, the more the wind pressure coefficients are decreased. When approaching flow angle is 45° or 67.5°, it is turned to negative pressure. Because internal pressure is determined by the difference of flow resistance between upstream and downstream, when pressure loss coefficients of flow passage from the windward opening to the leeward opening shown in Table 3 are observed, the more the approaching flow angle is increased, the more the pressure loss coefficient at the leeward opening is increased, and pressure loss coefficient when approaching flow angle is 45° is rapidly increased compared with the value of 1.45 when the approaching flow angle is 22.5°. This agrees well with the findings by Akabayashi et al.[1] If indoor wind pressure change associated with the change of approaching flow angle is taken into consideration, in case approaching flow angle is 45° or more, it is estimated that flow resistance at the windward opening is high, and there is no difference in flow resistance at the leeward opening.

3-2-2 Ventilation Rate at Leeward Opening of Each Building in case Approaching Flow Angle is Different

The ventilation rate at the leeward opening of SS model and KYO model shown in Table 3 is decreased when the approaching flow angle is increased. In case of SS model, if ventilation rate when approaching flow angle is 0° is taken as reference, ventilation rate is decreased by 3% when approaching flow angles is 22.5° and by 9% when it is 45°, but there is no substantial difference. On the other hand, if the ventilation rate of KYO model when approaching flow angles is 0° is taken as reference, it is decreased by 5% and 28% respectively. In case of SS model, this agrees well with the findings of Akabayashi et al.[1] in that ventilation rate is not changed almost at all up to the approaching flow angles of 45°. According to their study, ventilation rate tends to decrease when the approaching flow angles is 45° or more. When the approaching flow angles reaches 45°, pressure loss coefficient is somewhat increased compared with the case where approaching flow angles is 0° or 22.5°. This is due to the increase of pressure loss coefficient at the windward opening because internal pressure is turned to negative pressure when the approaching flow angles is 45°. This may be primarily attributable to the fact that wind direction of the approaching flow is maintained in the main airflow path even when wind direction is changed and the increase of the approaching flow angle has the same effect as the reduction of the opening area. On the other hand, at the leeward opening, indoor airflow is accelerated again and flows out, and the influence of wind direction is relatively low.

3-2-3 Main Airflow Path in Building when Approaching flow angles is Different

Figure 12 shows air velocity distribution at the central height of SS model when approaching flow angle is changed by every 22.5°. When main airflow path is observed in case approaching flow angles is different, it runs straightforward after entering in when approaching flow angle is 22.5°, and, after reaching the lateral wall, wind direction is gradually turned toward the leeward opening and it flows out. Indoor airflow is turned to recirculating flow turning counterclockwise, and the center of the circulation is located at the center of the room. In case approaching flow angles is 45° and 67.5°, the aspect of the airflow is similar to each other. In the windward half-region in the room, it is turned to a flow running straightforward along the direction of the main airflow path, and to a flow running straightforward diagonally to the windward direction reverse to the above in the leeward half-region. In case approaching flow angles is 45°, air velocity is at the highest immediately after entering the windward opening. This appears to be comparable to the case where ventilation rate when wind direction is 45° is almost the same as the ventilation rate when it is 0°. On the other hand, in the air velocity distribution on vertical cross-section when approaching flow angle is 45°, from Figure 13 (cross-section A-A in Figure 12) based on numerical simulation and from Figure 14 showing the results of air velocity measurement in SS model and LL model, it is evident that the main airflow path in the models runs straightforward, and this is different from the case where inflow airflow runs downward on vertical cross-section of air velocity distribution when approaching flow angles is 0°.

4. CONCLUSION

On 5 types of building models having the same outline dimensions, wind tunnel experiment and numerical simulation were performed. The airflow characteristics in and around the building during ventilation have been discussed using the results of wind tunnel experiment and numerical simulation in case the opening conditions such as presence of opening, difference of opening area, etc. are different and in case approaching flow angle is changed by every 22.5°. The following findings were obtained:

1) In case the opening is positioned nearly at the center of windward or leeward walls and in case approaching flow angle is 0°, the difference of wind pressure coefficient between models is within 0.2 even when the opening conditions are different, and overall flow exhibits no substantial change around the building in case the opening conditions are within the range as discussed above. The airflow flowing through the windward opening runs down.
2) In case approaching flow angles is different, the more the approaching flow angle is increased, the more the wind pressure coefficient is decreased. The airflow running along the wall surface is turned in lateral direction. Air velocity is increased, and ventilation rate is decreased. When approaching flow angles exceeds 45°, flow resistance at the windward opening rapidly increases. In case the airflow enters without running perpendicularly to the windward wall, the airflow runs straightforward after entering the windward opening.

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