Workshop. Natural ventilation of buildings: numerical simulations and measurements

Airflow visualization and measurements of fluctuating flow using particle image velocimetry (PIV) for a model house with single-sided and cross-ventilation in a large boundary-layer wind tunnel

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SUMMARY

Particle image velocimetry (PIV), which has recently attracted considerable attention, was originally developed by improving PC performance and image processing. PIV is a noncontact method that measures the airflow velocity at multiple points simultaneously, thus, it is preferred over conventional anemometers. Cross ventilation is a nonsteady-state phenomenon, and to understand it better, the wind flow and velocity have to be quantified. This study describes the airflow distribution in a simple cross-ventilated house model by using PIV and a large-size boundary wind tunnel. Two house models were used in the experiments. The first model has two openings on opposite walls, and the second has two openings on the same wall. The visualization of cross ventilation is performed by using three lasers. The location of the openings and the wind direction are the experimental variables. The wind velocity and turbulent kinetic energy distribution in and around the model are reported.

INTRODUCTION

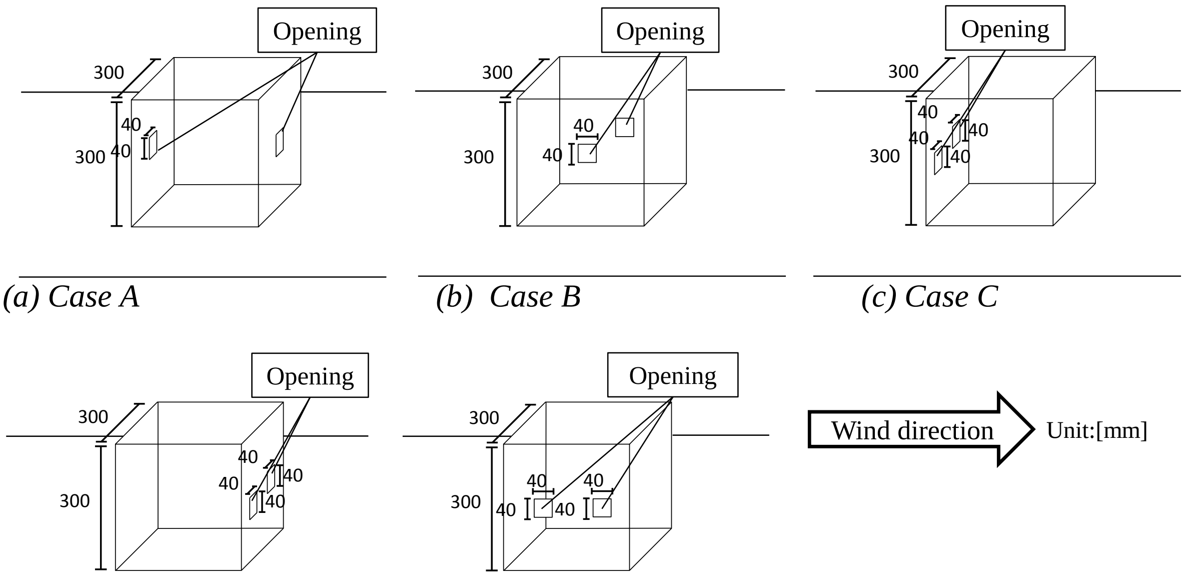
Cross ventilation in interior spaces is a commonly adopted means of providing natural ventilation in Japan during moderate seasons, including in the summer. Cross ventilation is a complex phenomenon. Flow visualization is used to analyse fluid flow phenomena, such as natural wind flow or air conditioner airflow. Several flow visualization method have been used in the past. In particle image velocimetry (PIV), which has recently attracted considerable attention (Kotani et.al. 2009, Akabayashi et.al. 2013), the flow of mixed minute particles (tracers) is visualized in a plane by a laser light sheet, photographing the movements of tracers by high-speed camera and calculating the flow velocity by performing digital image processing of the visualization images. PIV is a noncontact method that measures airflow velocity at multiple points simultaneously, thus, it is preferred over conventional anemometers.

This study describes the airflow distribution in a simple cross-ventilated house model by using PIV and a large-size boundary wind tunnel. Two house models were used in the experiments. The first model has two openings on opposite walls, and the second has two openings on the same wall (Sato 1937). The visualization of cross ventilation is performed by using three lasers. The location of the openings and the wind direction are the experimental variables. The wind velocity and turbulent kinetic energy distribution in and around the model are reported.

EXPERIMENTS AND ANALYSIS METHODS

Experimental house models

The experimental house models are constructed of transparent acrylic boards. The transparent acrylic boards are 3-mm thick. Two house models were used in the experiments. The first model, in Case A and B, has two openings on opposite walls, and the second, in Cases C, D, and E, has two openings on the same wall as shown in figure 1. The house model is 300 mm wide 300 mm high and 300 mm deep. The size of the opening as a window in the model's wall is 40x40 mm.



(a) Case A *(b) Case B* *(c) Case C*

(d) Case D *(e) Case E*

Figure 1. Experimental simple house model and relation between wind direction and openings of model.

Experimental conditions about measurement cases

The location of openings and the wind direction are the experimental variables as indicated in Table 1. Visualization by laser sheet and photographing by high-speed camera was performed in 5 house models.

Measurement cases are as follows:

Case A has one opening on the windward wall and another on the leeward wall.

Case B has one opening on one parallel wall to the wind direction and another opening on another parallel wall.

Case C has two openings on the windward wall.

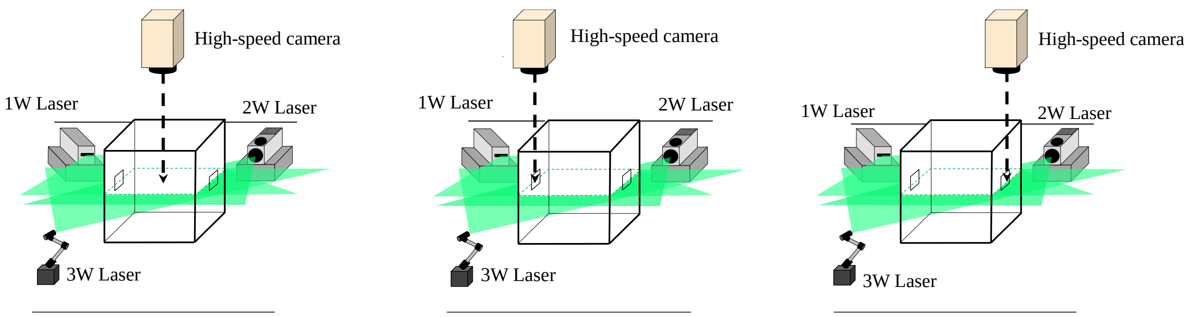
Case D has two openings on the leeward wall.

Case E has two openings on the wall parallel to the wind direction.

When we visualize and take images of the inside and outside of the model, the perspective effect occurs in the images. In the perspective effect, the interior wall is reflected and crowded in flow around openings, thus, it is very difficult to take clear images of the inlet and outlet of airflow in the model. In this study, two camera angles are set as indicated in figure 2. The first angle is set to the center of the model in order to measure the inside airflow, and the second angle is set to one opening in order to measure the inlet and outlet airflow. We aimed to take images inside and outside the model, and to measure by PIV regarding fluctuation of the wind direction and the wind velocity of inlet and outlet airflow.

Table 1. Experimental conditions of measurement cases

House model	Case	Measurement section	Camera angle
CaseA	A-1	Vertical section	Center of model
	A-2	Vertical section	Windward opening
	A-3	Horizontal section	Center of model
	A-4	Horizontal section	Windward opening
	A-5	Horizontal section	Leeward opening
CaseB	B-1	Horizontal section	Center of model
	B-2	Horizontal section	One opening
CaseC	C-1	Horizontal section	Center of model
	C-2	Horizontal section	Windward wall
CaseD	D-1	Horizontal section	Center of model
	D-2	Horizontal section	Leeward wall
CaseE	E-1	Horizontal section	Center of model
	E-2	Horizontal section	Side wall



(a) Case A-3 *(b) Case A-4* *(c) Case A-5*

Figure 2. Example of relation between camera angle and model (horizontal Section: Case A). The first angle (a) is set to the center of the model in order to measure the inside airflow, and the second angle(b),(c) is set to one opening in order to measure the inlet or outlet airflow.

Experimental equipment

When the model is irradiated by high output lasers, the laser light sheet is refracted at the joint of the model's wall and the edges of the openings made by the transparent acrylic board. Clear shadows occur in the measurement area. Consequently, as an unnatural difference of pixel intensity against the circumference occurs in the shadows, wrong vectors or no vectors are often calculated at measurement points in shadows. Therefore in this experiment, multiple lasers irradiate the model in order to eliminate the shadows. Three lasers that have outputs of 1W, 2W, and 3W are used. Three laser light sheets are adjusted on the same plane. To visualize the whole measurement area uniformly, a 3W-output laser irradiates the whole of the house model, and 2W-output and 1W-output lasers are placed on opposite sides and irradiate the house model as indicated in figure. 2. The high-speed camera used in this experiment is Photron FASTCAM-SA3 and PIV analysis is performed by Flow-Expert ver.

1.25 as indicated in table 2. The visualization images photographed by high-speed camera are 8-bit grayscale gradation images.

Table 2. Experimental equipment.

Camera	High-speed camera: Photron FASTCAM-SA3 1024 pixels×1024 pixels, 500fps, Shutter speed : S=1/500	
Laser	DPGL-3W	LD Excitation, Nd:YAG/YVO_4 Laser Wavelength: 532 nm, Output: 3 W Continuous light (Modulation range: 0〜30 kHz
	DPGL-2W	LD Excitation, Nd:YAG/YVO_4 Laser Wavelength: 532 nm, Output: 2 W Continuous light (Modulation range: 0〜30 kHz
	G1000	LD Excitation, Nd:YAG/YVO_4 Laser Wavelength: 532 nm, Output: 1 W Continuous light (Modulation range: 0〜30 kHz
Software	Camera control	Photron FASTCAM Viewer ver.3.3.8
	PIV analysis	Flow-Expert ver1.25

Details of experimental and analysis conditions

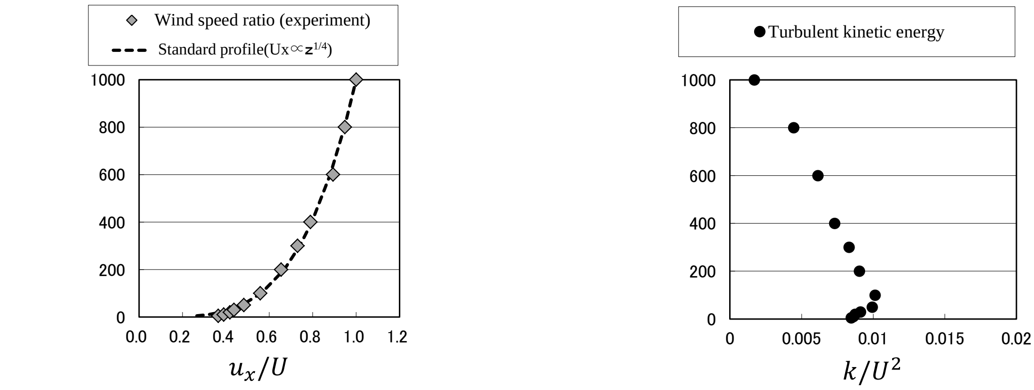
Experiments are performed using a large boundary-layer wind tunnel sized 1800 mm high and 1800 mm deep. The standard approach airflow is $U \propto Z^{1/4}$(U: wind velocity, Z: height). Approaching air flow profiles of large-size boundary layer wind tunnel are indicated in figure 3. The calibration value, which is the conversion value between the pixel length and the real size length, is 0.59 mm/pixel (vertical section), 0.66 mm/pixel (horizontal section) as indicated in table 3. The calibration value is calculated by installing and photographing a recognizable plate of real distance on the measurement area. The flame rate of the high-speed camera (measurement interval) is 2.0 ms (500 fps). Each measurement takes 16 seconds. Tracers are flame-retardant smoke made by a smoke generator: DAINICHI PORTA SMOKE PS-2002. The particle size is several tens μm or more. The smoke generator is placed to the windward so that it does not influence the airflow to the extent possible, and performs seeding. The standard wind velocity in the wind tunnel is 5.0 m/s at 1.0 m (height). The PIV analysis method is the direct cross-correlation method. The turbulent kinetic energy is calculated by equation. (1).

$$k= \frac{1}{N}\sum_{t=1}^{N}\left[\frac{1}{2}\left(\sum_{c=0}^{1}\{(c,\tilde{u}_i)-(c,u_i)\}\right)^2\right] \quad (1)$$

k:Turbulent kinetic energy [m^2/s^2], t:Time, N:Data number,
c:Component number (c=0 : x component, c=1 : y or z component),
i:Grid number, $\tilde{u}_i$: Instantaneous wind velocity, u_i: Mean wind velocity

Table3. Parameter of PIV analysis.

Case	Case A (Vertical section)	Case A〜E (Horizontal section)
Image size	1024 pixels×1024 pixels	1024 pixels×1024 pixels
Measurement range	604 mm×604 mm	674 mm×674 mm
Calibration value	0.59[mm/pixel]	0.66[mm/pixel]
Measurement time	16 sec	16 sec
Measurement interval	2.0 ms(500 fps)	2.0 ms(500 fps)
Interrogation region	27 pixels×27 pixels	19 pixels×19 pixels
Search region	±16 pixels×±16 pixels	±12 pixels×±12 pixels



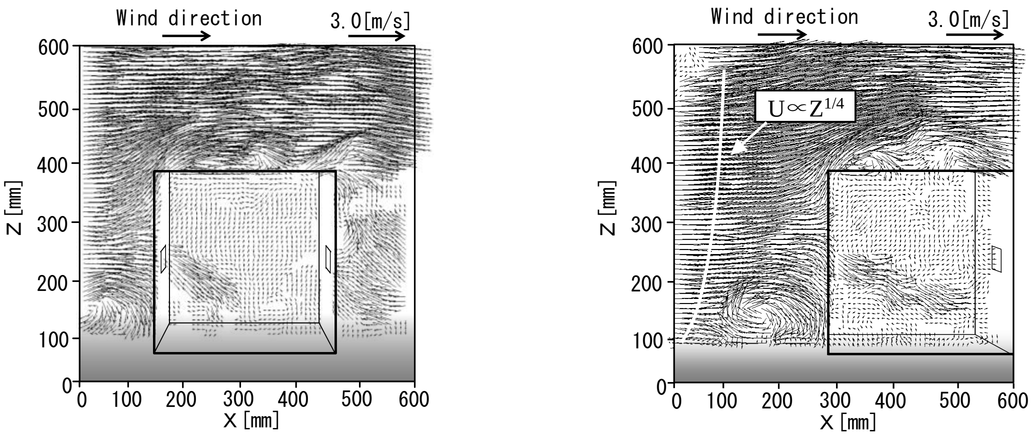
(a) Wind speed ratio u_x/U *(b) Turbulent kinetic energy*

Figure 3. Approaching air flow profile of large-size boundary layer wind tunnel.

RESULTS AND DISCUSSION

PIV analysis result in Case A (vertical section)

Figure 4 (a) shows that the wind velocity of the inlet airflow is about 0.8 m/s but the wind vector is not calculated near the windward opening. The mainstream of the wind velocity is about 0.4 m/s. The outlet airflow from the leeward opening has a wind velocity of about 1.3 m/s and rises in a slant direction. In figure 4 (b), approach wind flows from the windward direction. The airflow collides to the windward wall surface, drops along the wall surface and forms a vortex at a velocity from 1.0 to 2.0 m/s in X=80-280 mm and Z=100-170 mm. The inlet airflow flows at a velocity of 1.0 m/s to the downward direction through the opening. The wind velocity of the inlet airflow is from 1.4 to 1.8 m/s in the house model. Compared with Case A-1, airflow distribution is measured clearly in Case A-2 because no perspective effect occurs at the windward opening. A vortex is formed in the roof of the house model by the separation of the airflow.

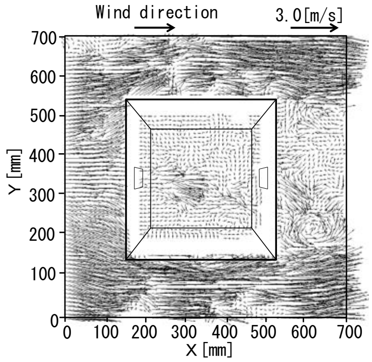


(a) Distribution of instantaneous wind velocity vector (Case A-1) *(b) Distribution of instantaneous wind velocity vector (Case A-2)*

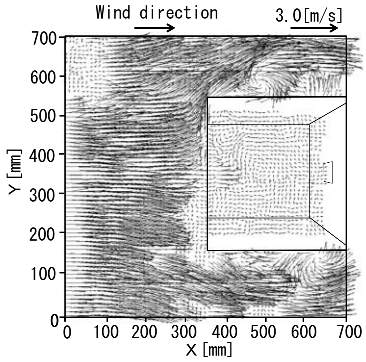
Figure 4. Result of PIV analysis in Case A (vertical section).

PIV analysis result in Case A (horizontal section)

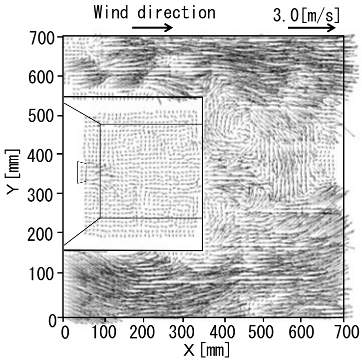
Figure 5(a) shows that the inlet mainstream of the wind velocity is about 1.0 to 2.0 m/s but the wind vector is not calculated near the opening. Airflow moves steadily into the model through the windward opening and sways from side to side. In figure 5(b), the wind velocity of the inlet airflow is about 1.0 to 2.0 m/s. In figure 5(c), the wind velocity of the outlet airflow is about 1.0 to 1.5 m/s. Airflow distribution is measured clearly at the windward and leeward opening. Complex airflow is formed at wake due to outlet airflow mixing with outside airflow.



(a) Distribution of instantaneous wind velocity vector (Case A-3)



(b) Distribution of instantaneous wind velocity vector (Case A-4)

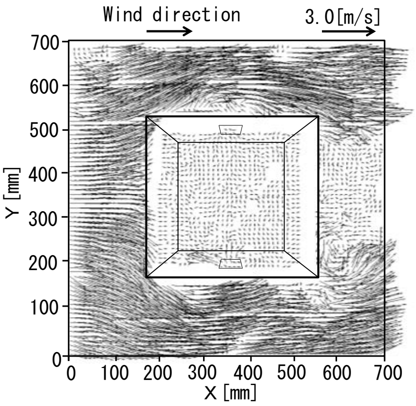


(c) Distribution of instantaneous wind velocity vector (Case A-5)

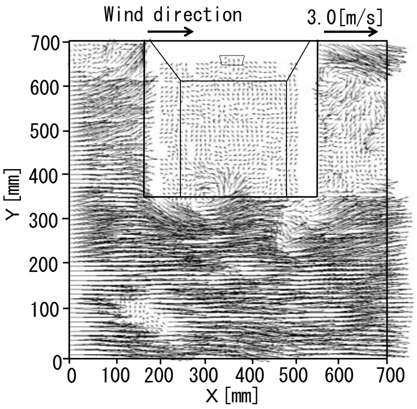
Figure 5. Result of PIV analysis in Case A (horizontal section).

PIV analysis result in Case B (horizontal section)

Figure 6(a) shows that airflow moves into the room model through one opening and another one in turn. The wind velocity of inlet airflow is about 0.5 to 1.0 m/s. The wind velocity of outlet airflow is about 0.5 to 0.8 m/s. In figure 6(b), the wind velocity of inlet airflow is about 0.5 to 1.0 m/s.



(a) Distribution of instantaneous wind velocity vector (Case B-1)



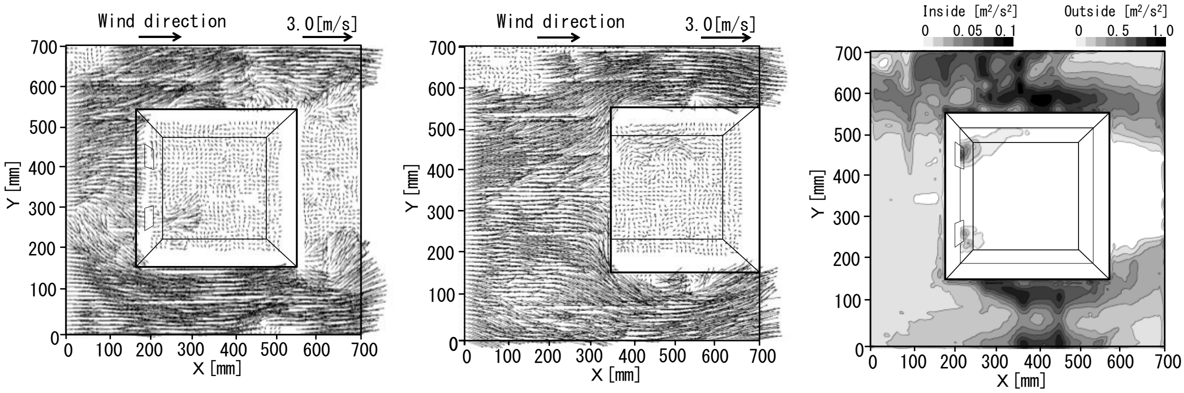
(b) Distribution of instantaneous wind velocity vector (Case B-2)

Figure 6. Result of PIV analysis in Case B (horizontal section).

PIV analysis result in Case C (horizontal section)

In figure 7(a), (b), airflow flows into and out of the model in turns through two openings on the windward wall. The inlet airflow wind velocity is 1.0 m/s and the outlet wind velocity is from 0.5 to 0.8 m/s.

Figure 7(c) shows that the distribution of the turbulent kinetic energy is from 0.05 to 0.2 m^2/s^2 at the outside of the windward and leeward wall. In the house model, the turbulent kinetic energy is from 0.01 to 0.05 m^2/s^2 at the mainstream around the two openings, and it is almost 0 m^2/s^2 in all domains except for the mainstream.

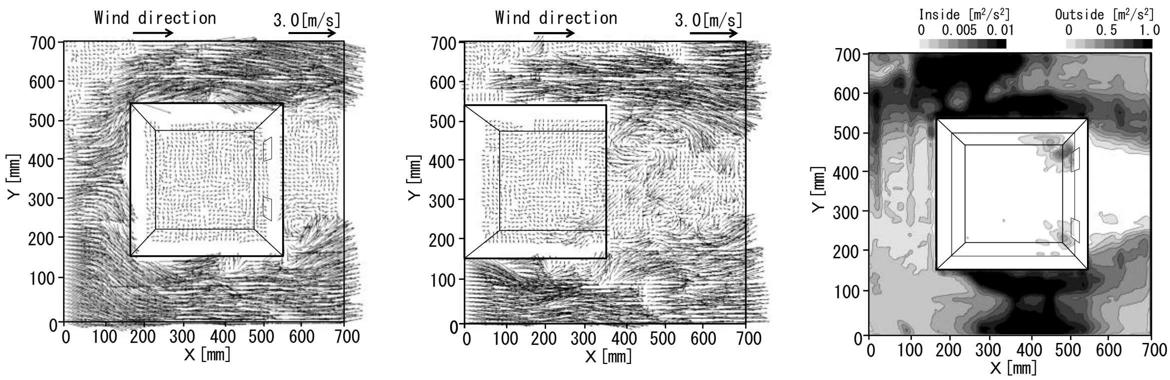


(a) Distribution of instantaneous wind velocity vector (Case C-1)
(b) Distribution of instantaneous wind velocity vector (Case C-2)
(c) Distribution of turbulent kinetic energy (Case C-1)
Figure 7. Result of PIV analysis in Case C (horizontal section).

PIV analysis result in case D (horizontal section)

In figure 8(a), airflow flows into and out of the model in turns through two openings on the leeward wall. The inlet and outlet airflow wind velocity is 0.3 to 0.5 m/s. In figure 8(b), the inlet and outlet airflow wind velocity is 0.5 to 1.0 m/s. Compared with Case D-1, airflow distribution is measured clearly at the leeward opening in Case D-2.

Figure 8(c) shows that the turbulent kinetic energy is from 0.001 to 0.005 m^2/s^2 at the mainstream around the two openings in the house model. Turbulent kinetic energy in house model of case D is less than other cases.

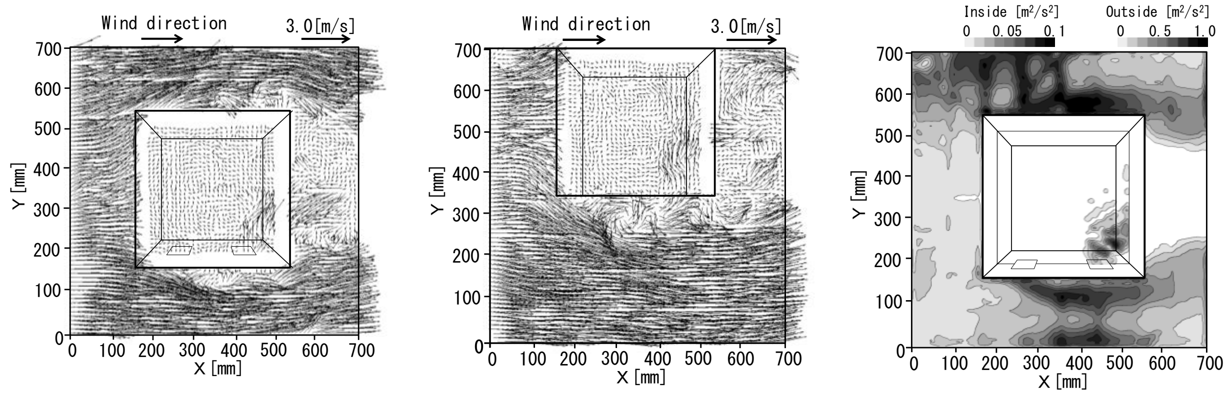


(a) Distribution of instantaneous wind velocity vector (Case D-1)
(b) Distribution of instantaneous wind velocity vector (Case D-2)
(c) Distribution of turbulent kinetic energy (Case D-1)
Figure 8. Result of PIV analysis in Case D (horizontal section).

PIV analysis result in case E (horizontal section)

Figure 9 (a) shows that airflow flows into the model through the leeward opening at 0.8 to 1.3 m/s. In figure 9 (b), vortexes of which the wind velocity is from 0.8 to 1.5 m/s are formed by separation of the airflow around the wall parallel to the wind direction. Airflow of which the wind velocity is from 0.8 to 1.5 m/s flows into the model through the leeward opening, so the airflow flows to the opposite wall. The outlet airflow is 1.0 m/s through the windward opening.

In figure 9(c), the distribution of turbulent kinetic energy is from 0.05 to 0.2 m^2/s^2 at the outside of the windward and leeward wall. In the house model, the turbulent kinetic energy is from 0.02 to 0.08 m^2/s^2 around the leeward opening. The turbulent kinetic energy is almost 0 m^2/s^2 in all domains except for the mainstream.



(a) Distribution of instantaneous wind velocity vector (CaseE-1)

(b) Distribution of instantaneous wind velocity vector (Case E-2)

(c) Distribution of turbulent kinetic energy (Case E-1)

Figure 9. Result of PIV analysis in Case E (horizontal section).

CONCLUSION

In Case A (two openings on opposite windward and leeward walls)

The airflow collides at the windward wall surface and drops along the wall surface and forms a vortex at a velocity from 1.0 to 2.0 m/s.

In Case B (two openings placed on opposite walls parallel to wind direction)

Airflow moves into the room model through one opening and another one in turn.

In Case C (two openings placed on windward wall) and Case D (two openings placed on leeward wall)

Airflow moves into and out of the model through the openings on the same wall in turn. Turbulent kinetic energy in house model of case D is less than other cases.

In Case E (two openings on parallel wall to wind direction)

Airflow of which the wind velocity is from 0.8 to 1.5 m/s flows into the model through the leeward opening, so the airflow flows to the opposite wall. The outlet airflow is 1.0 m/s through the windward opening.

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