

EXPERIMENT OF THE MIXING PROPERTY AND THE HEAT EXHAUST EFFECT UNDER CROSS VENTILATION IN A FULL-SCALE BUILDING MODEL

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ABSTRACT

Cross ventilation is one of the most important techniques for achieving energy conservation and for maintaining a comfortable indoor environment in summer. But it is difficult to evaluate the effect of cross ventilation quantitatively and to design based on a quantitative evaluation, because the indoor environment is uneven and changes with the outside conditions under cross ventilation.

The full-scale model experiment has been done under cross ventilation, and the properties of airflow in and around the full-scale model have been examined. In this paper, the mixing property and heat exhaust effect of cross ventilation are discussed.

Concentration decay in the full-scale model is measured by using tracer gas technique, and the spatial unevenness of mixing property is examined. And it is shown that the different mixing properties are formed with the airflow pattern. In the experiment of the heat exhaust effect, the temperature of air and surface and exhaust heat is measured. The relation between the temperature reduction and the flow path is examined. Two experiments show that ventilation rate is the most effective factor to decide the exhaust heat and the room mean age of air. But air flow pattern also has an influence.

KEYWORDS

Cross ventilation, Full-scale model experiment, Mixing property, Heat exhaust effect

INTRODUCTION

Cross ventilation driven by wind is one of the most important techniques for achieving energy conservation and for maintaining a comfortable indoor environment in summer for the temperate regions. But it is difficult to evaluate the effect of cross ventilation quantitatively and to design based on a quantitative evaluation, because the indoor environment has unevenness and changes dynamically with outside conditions under cross ventilation. It is difficult to predict the air flow rate under cross ventilation due to variational wind. And it is still difficult to estimate indoor comfort condition given by cross ventilation.

In the previous study, the full-scale model experiment has been done under cross ventilation, and the properties of air flow (velocity field, pressure distribution on surface, discharge coefficient of openings, ...) have been examined. In this paper, it is discussed the influence of the air flow pattern on the mixing property and heat exhaust effect under cross ventilation.

EXPERIMENTAL METHOD

The plan and section of the wind tunnel for cross ventilation is shown in Figure 1. The wind tunnel was constructed to examine the property of air flow in and around a full-scale building model. Its form is different to a conventional boundary layer wind tunnel, but it is possible

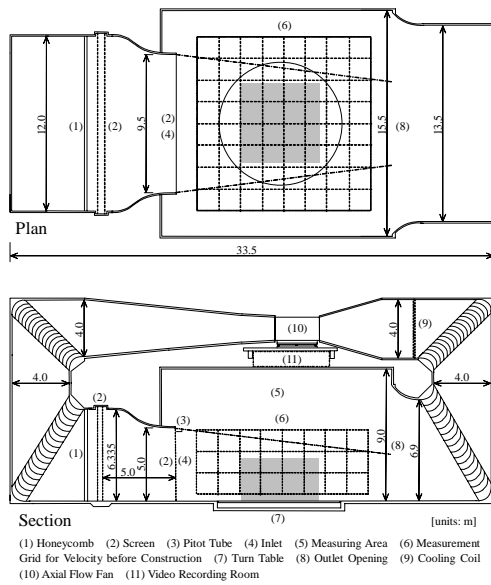


Figure 1: Plan and section BRI's cross ventilation laboratory wind tunnel

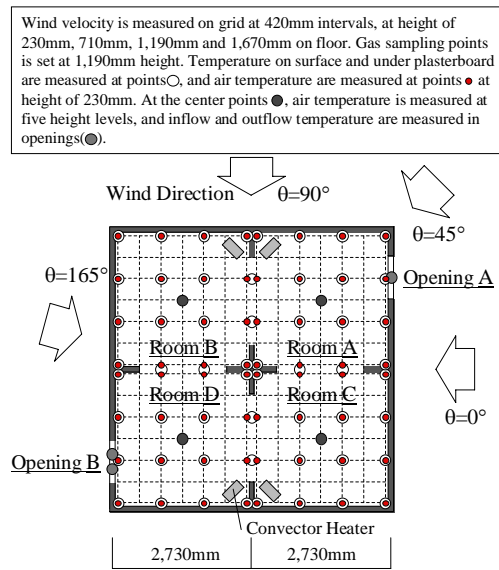


Figure 2: Building model and measuring points

that the full-scale building model gets same wind pressure condition repeatedly. In the wind tunnel, the air flow pattern and the wind pressure has already been measured in detail. The building model is shown in Figure 2. It has dimensions $W=D=5,560\text{mm}$ and $H=3,000\text{mm}$ and has four rooms. It has two large openings ($W=860\text{mm}$, $H=1,740\text{mm}$), which are set at diagonal position of the model for cross ventilation. Wind direction is set at every 15 degree ($0^\circ - 165^\circ$) by rotating the model. Air flow velocity is measured on indoor grid using 3-dimensional ultrasonic anemometer (Kaijo, WA-390). The average velocity at the inlet is set at 3m/s.

The automatic doors are set at both openings in the experiments of the mixing property and heat exhaust effect. The mixing property in the uneven space under cross ventilation is evaluated applying repeatedly the tracer gas technique with changing the door-opening interval. The concentration decay is measured at 0.05 sec intervals at 17 or 18 sampling points, which are set at 1,190mm height every wind direction. And the average concentration decay is also measured at intervals of door-opening setting.

In the experiment of the heat exhaust effect, foam plastic insulation boards 50mm thick are set on floor, wall and ceiling in the model, and plasterboards 12.5mm thick are set on floor as thermal storage. Before opening the doors, indoor air is heated evenly about 10 degrees centigrade higher than wind tunnel temperature by using heaters and mixing fans. And the change of temperature of air and floor surface is measured every 15 seconds at points in Fig.2 after opening the doors.

RESULTS

Mixing Property

The results of typical three cases (Wind directions are 15° , 45° and 105°) are shown in Figure 3–11. Figure 3 shows the visualized flow pattern in 15° . Figure 4 shows the air flow field in and around the model at 1,190mm height and the local air change index (ϵ_p) at sampling points. And Figure 5 shows the decay of normalized concentration at some points. In the case of wind directions 15° , the main current appears clearly, and the concentration decrease

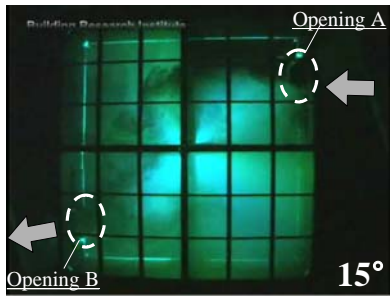


Figure 3: Air flow visualization (15°)

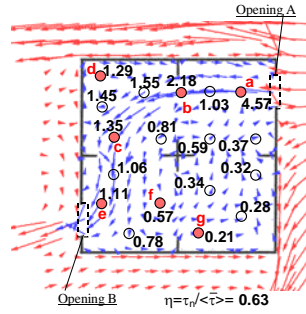


Fig. 4: Sampling points and local air change index (15°)

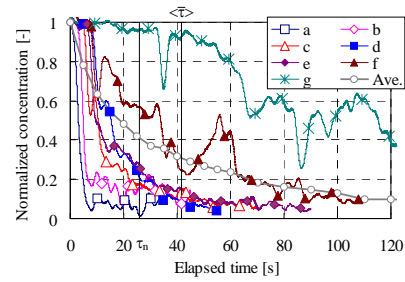


Fig. 5: Concentration decay (15°)

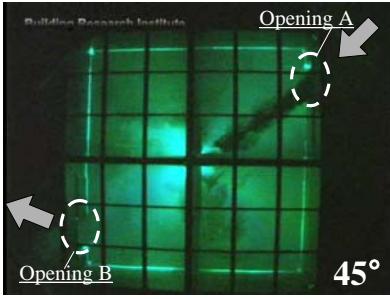


Figure 6: Air flow visualization (45°)

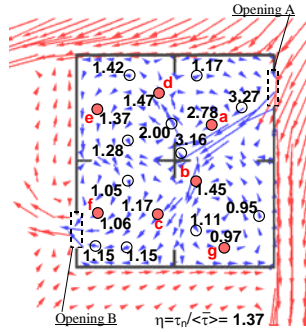


Fig. 7: Sampling points and local air change index (45°)

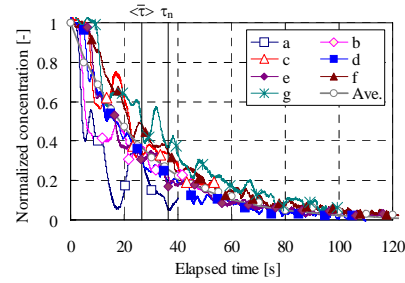


Fig. 8: Concentration decay (45°)

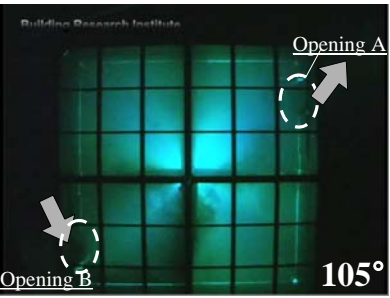


Figure 9: Air flow visualization (105°)

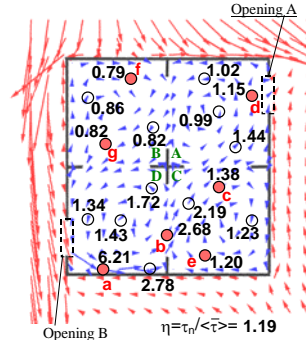


Fig. 10: Sampling points and local air change index (105°)

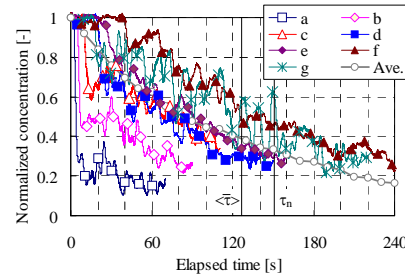


Fig. 11: Concentration decay (105°)

quickly at the points in main current (point **a**, **b** in Figure 4 and 5). In the edge of the main current (point **f**), the concentration decay is slow, and has large periodic fluctuation. The periodic fluctuation is caused by vortices, which are made by mixing of main current and retention air (Figure 3). At point **g**, which is far from main current, the concentration attenuates very slowly (Figure 5). The average concentration decay is also shown in Figure 5. In the case of wind direction 15°, the room mean age of air ($\langle \tau \rangle$) is 41.5s, and the coefficient of air change performance (η) is 0.63. This is the similar characteristic of poor mixing ventilation and shows the tendency that the air in the main current is smoothly discharged, and the air is kept in the retention area for a long time.

In the case of wind direction 45°, the current collides with the pillar and walls at center in the model, and diverges in two directions (Figure 6, 7). The coefficient of air change performance (η) is 1.37, and the air flow field shows the characteristic of the piston flow (Figure 7). There is not so much of difference in the speed of concentration decay, except points **a**, **b** (Figure 8). And the distribution of the local air change index (ϵ_p) is more even than wind direction 15°. Therefore, indoor air is discharged effectively ($\langle \tau \rangle_{(15^\circ)}=41.5s$, $\langle \tau \rangle_{(45^\circ)}=28.5s$) though the air flow rate in 45° is smaller than 15° ($Q_{(15^\circ)}=9,700m^3/h$, $Q_{(45^\circ)}=7,000m^3/h$).

In the case of wind direction 105° (Figure 9 – 11), the air flow rate is smaller ($Q_{(105^\circ)}=1,700\text{m}^3/\text{h}$), and the room mean age of air is longer ($\langle\bar{\tau}\rangle=126.4\text{s}$) than 15° and 45° . The coefficient of air change performance (η) is 1.19, and the total mixing property in the model is close to the perfect mixing, but the distribution of the local air change index (ε_p) shows the unevenness along the flow (ε_p has the tendency of Room **D** > **C** > **A** > **B** (Figure 10)). The concentration at point **g** has large periodic fluctuation because of air exchange between Room **C** and **B** (Figure 10, 11).

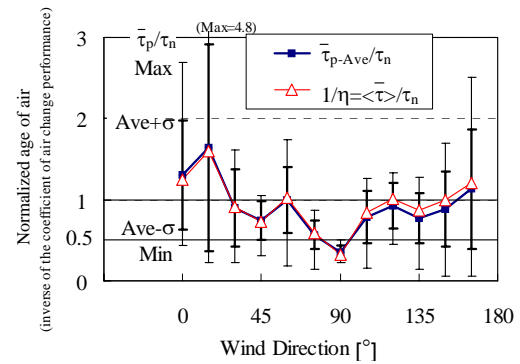


Figure 12: Distribution of local mean age of air

Figure 12 shows the age of air normalized by the nominal time constant (τ_n). When the value of normalized room mean age of air ($\langle\bar{\tau}\rangle/\tau_n$) becomes larger (η becomes smaller), the difference of $\bar{\tau}_p$ between the sampling points becomes larger, and the unevenness of mixing property between main current and retention area makes clear in the space. And when $\langle\bar{\tau}\rangle/\tau_n$ approaches 0.5 (η approaches 2) and the air flow field comes to show the tendency of the piston flow, the difference of $\bar{\tau}_p$ becomes small, and mixing property is formed uniformly.

Heat Exhaust Effect

Air temperature distribution (height of 230mm above floor level) and temperature distribution on floor surface in the case of wind direction 15° are shown in Figure 13, 14. Temperature is expressed normalized by initial inside-outside temperature differences. In the case of wind direction 15° , Air temperature quickly falls in the main current, and decreasing rate of air temperature is smaller in the retention area and at the back of pillar and side walls. The temperature of floor surface falls slower than the air temperature. The normalized temperature on floor is 0.6 - 0.8 at 5 minute after opening doors, and still keeps 0.2 – 0.3 under the main current and about 0.5 in the retention area 20 minutes later.

Figure 15 shows the exhaust heat from inside the model and the heat flow from floor in wind direction 15° . The exhaust heat flow H [W/K], which is normalized by initial inside-outside temperature differences, is obtained by follows.

$$H = \rho C_p Q(T_{\text{out}} - T_{\text{in}})$$

Where ρ is air density [kg/m^3], C_p is heat capacity of the air at constant pressure [$\text{J}/\text{kg K}$], Q is air flow rate [m^3/s], and T_{in} and T_{out} is the normalized temperature in the inflow and outflow [-]. Air flow rate Q was measured by integrating the velocity at 48 points in opening area. And the normalized heat flow from floor H_f [W/K] is calculated by follows.

$$H_f = \Sigma h A(T_f - T_a)$$

Where h is the convective heat transfer coefficient [$\text{W}/\text{m}^2\text{K}$], A is surface area [m^2], T_f is the normalized temperature on the floor surface [-] and T_a is the normalized temperature of air at height 230mm [-]. The convective heat transfer coefficient h was calculated from the moisture transfer coefficient, which is measured by evaporation from the filter paper at 196 points on floor in the wind direction 15° . Figure 16 shows the distribution of the convective heat transfer coefficient in the case of wind direction 15° . The convective heat transfer coefficient is high under main current, and it has higher value at collision point at sidewall (**a** in Figure

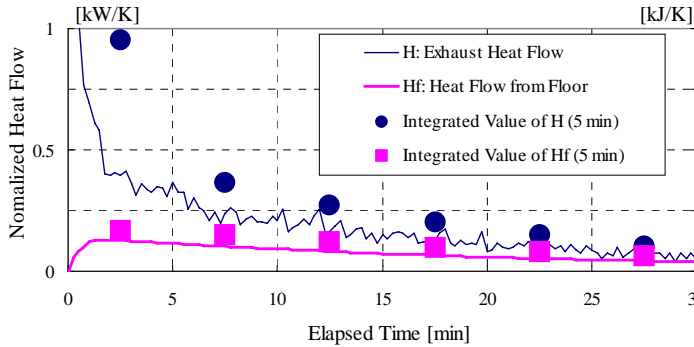
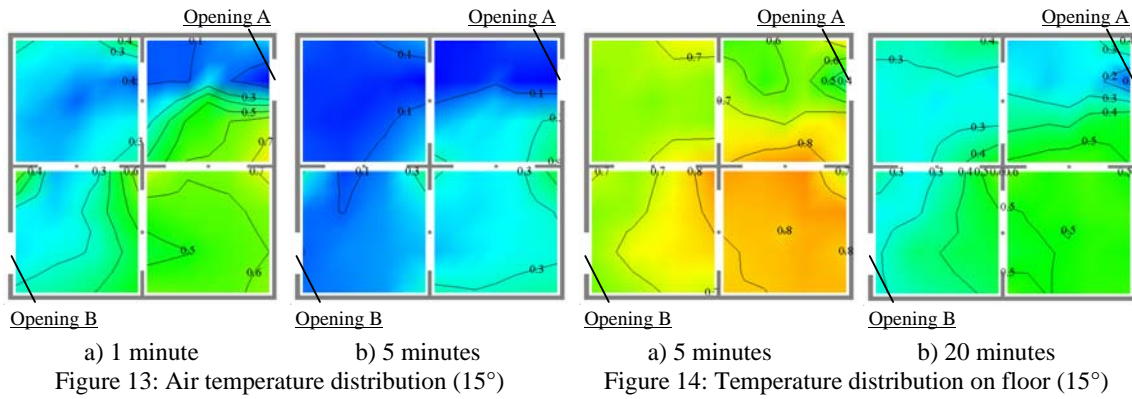


Figure 15: Heat transfer in 15°

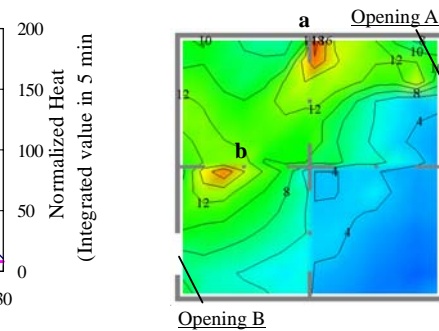


Fig.16: Distribution of the convective heat transfer coefficient (15°)

16) especially. Another higher point is influenced by pillar **b**. In Figure 15, the heat flow from floor (H_f) is smaller than the exhaust heat flow (H). Total H_f is only 40% of total H , because of the heat capacity other than plaster boards, aluminum sash and glass of partitions, and heat bridge of the frame. In the experiment, insulation boards are set on floor, walls, and ceiling, but don't covered partitions that are made of aluminum frame and glass. And the partitions are connected with steel frame and heat bridge is formed through insulation division. Therefore partitions keep large amount of heat before opening doors, and supply heat to ventilated air. Figure 17 shows the total exhaust heat normalized by initial temperature differences and the summation of heat capacity in insulation division of the model. Total H_f in 15° is almost equal to the heat capacity of plaster boards on the floor, so the experiment and the convective heat transfer coefficient is appropriate. Total H is uneven in the condition of wind direction, compared with the heat capacity in the insulation division, because of influences of the heat capacity of the ceiling and underfloor space that is connected by heat bridge.

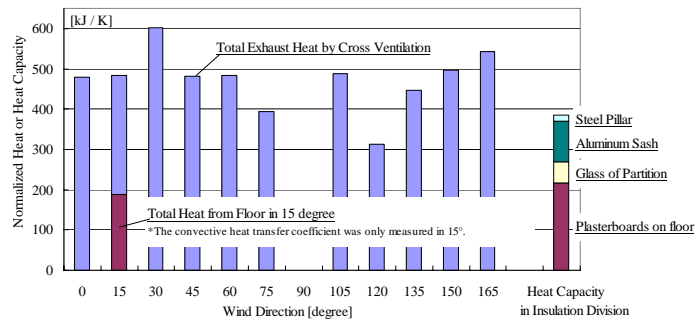


Figure 17: Total exhaust heat and heat capacity of the model

Figure 18 shows the relation between the air flow rate Q and the summation of exhaust heat H for 5 and 10 minutes from opening the doors (wind directions are shown in []). It is shown that the ventilation rate is the most effective factor to decide the exhaust heat. And there is little difference in the wind direction at low ventilation rate, but there is difference in the wind direction at high ventilation rate; internal heat is smoothly exhausted in 30° and 45°, and not

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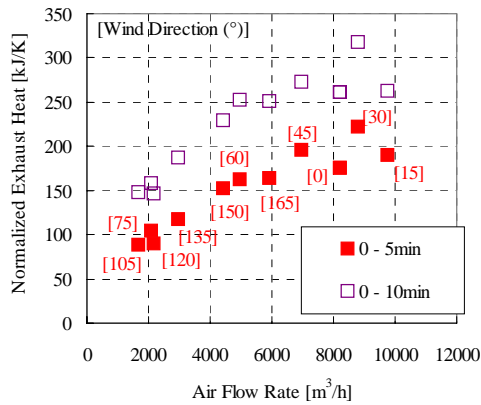


Figure 18: Air flow rate and exhaust heat

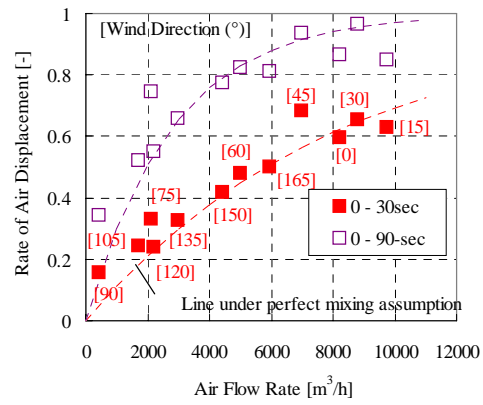


Figure 19: Air flow rate and air displacement

easily exhausted in 0° and 15° . The difference also appears in the rate of air displacement in the experiment of mixing property (Figure 19), and it is considered that the air flow pattern have an influence on the indoor convective heat transfer as well as the mixing property.

CONCLUSIONS

The mixing property and heat exhaust effect are examined experimentally in the uneven space under cross ventilation. Conclusion is as follows.

- 1) Relation between air flow pattern and mixing property is examined by the concentration decay. In the case that the main current appears clearly, the coefficient of air change performance (η) becomes smaller, and the uneven distribution of the local air change index (ϵ_p) appears clearly, and the speed of decay is different in measurement point. In the case that the airflow field has the characteristic of the piston flow, the coefficient of air change performance (η) approaches 2, and the distribution of the local air change index (ϵ_p) becomes uniform.
- 2) Temperature distribution of air and floor surface is measured and air temperature in main current decrease quickly. And the temperature on floor falls slower than air temperature, but the temperature under main current has faster decrease than the temperature in retention area reflecting the distribution of convective heat transfer coefficient.
- 3) The exhaust heat speed and the rate of air displacement are mainly affected by ventilation rate, but are reflected the difference of air flow pattern at large ventilation rate.

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