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Study on Cross-Ventilation Performance of Residences in the Passive Town Kurobe Model Based on Measurements and CFD

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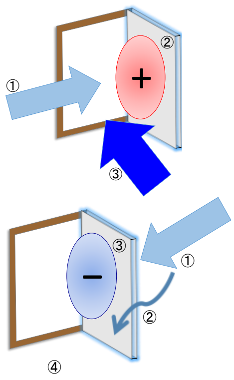
The housing complex in the Passive Town Kurobe model was designed for residents to enjoy an environmentally-friendly lifestyle, and cross-ventilation was used to improve indoor thermal environment in hot seasons. To understand and maximize environmental improvements through cross-ventilation, computational fluid dynamics (CFD) simulations and measurements were carried out. It was confirmed that CFD simulation using the modified k-ε model reproduced the observations with sufficient accuracy. The turbulence model used in the CFD simulations in this study was the standard k-ε model, which incorporates the Durbin limiter. This model had the most accurate correspondence with the measured values. The wind catcher (WC) used to increase the cross-ventilation flow rate was found to be ineffective in the dominant wind direction. Further, it was found that if the room targeted for environmental improvement was on the upstream/downstream side, the flow rate was maximized if all windows in the room were opened.

1 Introduction

There is increasing interest in passive houses that efficiently use natural energy and are superior in comfort, health, and energy conservation.

The 1st and 2nd blocks in the Passive Town Kurobe model were designed to distribute ventilation throughout the entire house using window arrangements and a wind catcher (WC; Fig. 1). The seasonal wind in this area has been considered previously, but the effect of opening specific windows was not clear.

Therefore, based on a comparison with actual measurements, it was necessary to understand the predictive accuracy of ventilation performance via computational fluid dynamics (CFD) analysis and to determine whether opening windows (and which ones to open) would affect ventilation.



①External wind collides with wind catcher
②Increase of wind pressure near the opening
③Increase of inflow air volume
①External wind collides with wind catcher
②Peeling off airflow
③Reduction of wind pressure near the opening
④Increase in outflow volume

Fig.1. Wind catcher

2 Outline of measurements and CFD analysis

2.1 Measurement overview

Fig. 2 shows a plan view of a target dwelling unit on the second floor of the 1st block, and Fig. 4 shows the type of window used. For the first block area, LDK-I side and private room 1 were considered.

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Fig. 3 shows a plan view of the target dwelling unit on the 4th floor of the 2nd city block, and Fig. 5 shows the window type used in the room in Fig. 3. For the second block area, the LDK on the south side of the dwelling unit was considered. In the second block, the inflow and outflow openings were selected from window 8-I at the end of the corridor, window 5-F of room 5, window II-H of the LDK, window II-G and window II-H. The difference in opening way was considered.

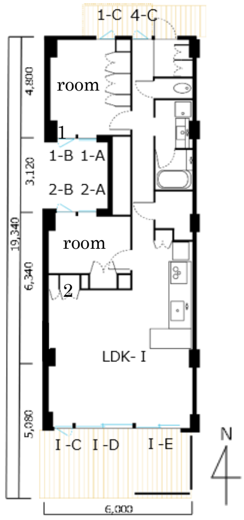

Fig. 2. Second floor of the dwelling unit of the first block Plan view (Unit: mm)

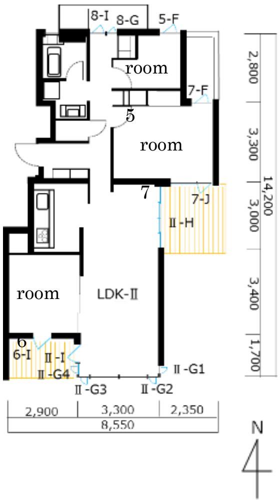

Fig. 3. Fourth floor of the dwelling unit of the second block Plan view (Unit: mm)

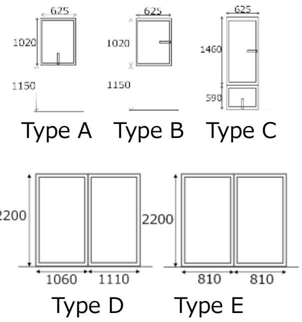

Fig. 4. First city block examination window (Unit: mm)

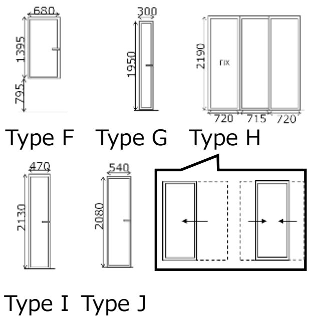

Fig. 5. Second city block examination window (Unit: mm)

Measurements were made using a wind direction anemometer installed on the roof of the residential building in the 1st block and on the roof of the neighboring company house in the 2nd block. For the indoor wind speed measurement, an omni-directional anemometer was used, and in the 1st block, wind speeds were measured in room 1 and the LDK-I; in the 2nd block area, measurements were taken in the LDK-II. In addition, the ventilation rate was measured using an ultrasonic anemometer, and the wall pressure difference between the outdoor wall surface near the opening and the indoor wall surface was measured with a differential pressure transducer.

2.2 CFD analysis

After analysis (model L), which reproduced 1,000 m^2 of the urban area surrounding the study target building, we analyzed the boundary condition of the reduced calculation area (model S) around the target building via data mapping.

The conditions analyzed are given in Table 1 for the 1st block and in Table 2 for the 2nd block. The target wind direction was set to 0° (north), 22.5°, 45°, and 270° based on the summer wind direction of the breeze map for Kurobe (Fig. 6). For the inflow boundary condition of model L, the approach flow measured by the wind tunnel experiment was used.

Table1. First block district analysis target conditions

Case name		Inflow opening	Outflow opening	Wind direction angle
case I -1	I -1-a	1-C-up	I -C-up	0°,22.5°
	I -1-b		I -C-down	22.5°
	I -1-c		I -E	0°,22.5°
case I -2	I -2-d	1-B	I -E	270°

Table2. Second block district analysis target conditions

Case name		Inflow opening	Outflow opening	Wind direction angle
case II -1	II -1-a	8- I	II -H(1 opening)	22.5°
	II -1-b		II -H(2 opening)	22.5°
case II -2	II -2-d	5-F	II -H(2 opening)	22.5°,270°
case II -3	II -3-a	8- I	II -G1	45°
	II -3-b		II -G2	270°
	II -3-c		II -G3	45°,270°
	II -3-d		II -G4	0°,270°

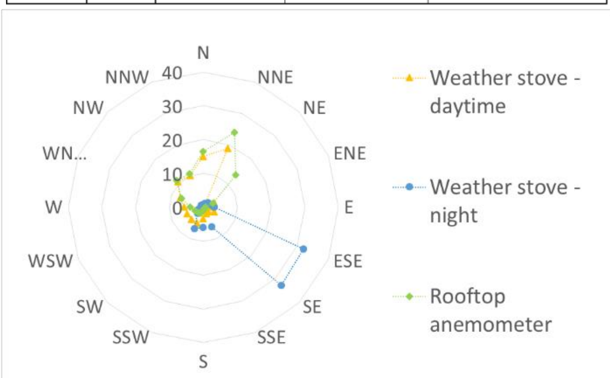

Fig.6.Wind direction map for Kurobe

3 Results of Measurements and CFD analysis

We investigated the appropriate turbulence model using the 2nd block. The turbulence models compared included a standard k-ε model (hereinafter referred to as "improved k-ε model"), realizable k-ε model, SST k-ω model incorporating the Durbin limiter and SST k-ω model. The turbulent energy k and turbulent dissipation factor ε obtained in model L were converted to the specific dissipation factor ω and mapped.

Fig. 7 shows a comparison of the results of analysis of each turbulence model as compared to actual measurements.

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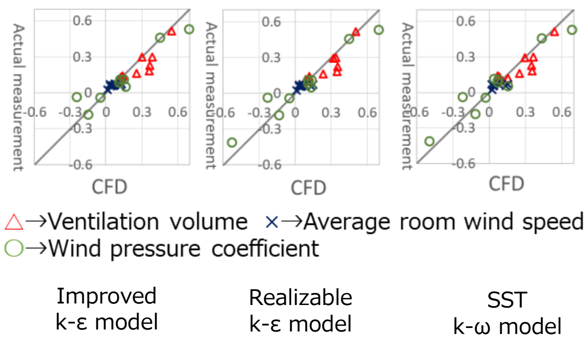

Fig.7. Comparison of analysis results for different turbulence models

4 Evaluation of ventilation performance by opening windows and proposal for improvement

4.1 Study of Effectiveness of the WC using CFD

The wind pressure difference acting on the opening is the driving force. Because the WC is a device used to stop the air flowing along the outer wall and to convert the dynamic pressure into wind pressure, the direction of installation with respect to flow is important. Figs. 8 through 9 show the opening wind pressure coefficients according to the presence or absence of the WC in the wind direction called “Ai no kaze” in the Kurobe area, i.e., at 22.5° and 135°.

We first consider the 1st block.

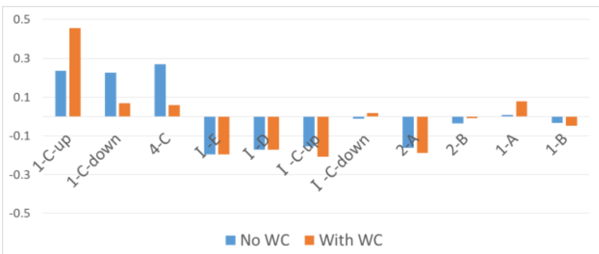

Fig. 8. Wind pressure coefficient near the opening of the first block (wind direction 22.5°)

When the wind direction is 22.5°, the wind flows from west to east due to the wind reflected from east to west on the windward side and the second downtown area on the leeward side. As is clear, the WC increases the positive pressure on window 1-C up, but it decreases the positive pressure at windows 1-C down and 4-C (Fig. 8). When installing the WC in the opposite direction, it is difficult to improve the ventilation performance because the WC exerts the opposite effect when wind flows in the same side.

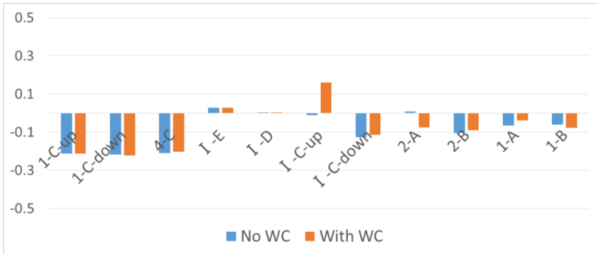

Fig. 9. Wind pressure coefficient near the opening of the first block (wind direction 135°)

For a wind direction of 135°, the wind flows from east to west, so the positive pressure increase determined by the WC on window I-C up is remarkable.

4.2 Ventilation performance evaluation method

With ventilation, the goal is to ensure that a large amount of natural ventilation occurs by opening windows, such as in the middle of a summer night, thereby allowing residents to directly force air currents and improve the environment by cooling the indoor air. With regard to air currents, the indoor airflow velocity is a standard, but in order to cool the indoor air, it is necessary to consider that the ventilation effect decreases as hot air on the upstream side of the ventilating room flows to the downstream side. Therefore, when assuming a constant contamination occurrence per unit volume in the entire ventilated housing space, the amount of effective ventilation obtained by dividing the contaminant generation amount of the target area by the average concentration of the area is converted into an effective ventilation frequency and evaluated (Table 3).

Table 3. Expressions for the evaluation method

$CQ = M \quad \rightarrow \quad Q = \frac{M}{C}$ $Q_e = \frac{Generationvolumeoftargetroom\ :M}{Averageconcentrationoftargetroom\ :C}$ ・・(1) Effective ventilation frequency $N_e = \frac{Q_e}{V}$ ・・(2) Ventilation frequency per outflow volume $N = \frac{Q}{V}$ ・・(3) Total ventilation frequency $N_{all} = \frac{Q}{V_{all}}$ ・・(4)
C:Chamber concentration[ppm] Q:Ventilation volume[㎥/h] M:Generation amount[㎥/h] Q_e:Effective ventilation[㎥/h] N_e:Effective ventilation frequency[Times/h] V:Target chamber volume[㎥]

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4.3 Ventilation performance evaluation method

Table 6. Second city block average wind speed and ventilation frequency (wind direction 22.5°)

	Case number	North corridor window	5-F	7-F	7-J	Ⅱ-H1	Ⅱ-H2	LDK South Window	6-I	Average wind speed [m/s]		Effective ventilation frequency [Times/h]	
										Entire LDK	LDK South side	Entire LDK	LDK South side
	1							○		0.005	0.008	0.4	0.6
LDK	2	○						○		0.151	0.168	18.1	20.7
	3	○				○		○		0.171	0.152	29.3	32.4
	4	○	○				○	○	○	0.177	0.151	18.1	20.7
	5	○		○			○	○	○	0.187	0.166	17.0	16.6
	6	○	○	○	○	○		○	○	0.188	0.168	16.8	17.9
	7	○	○	○		○		○	○	0.197	0.175	16.4	16.4
	8	○	○	○			○	○	○	0.196	0.171	15.3	15.5
	9	○	○	○				○	○	0.170	0.185	16.1	18.6
	10	○	○	○			○	○		0.201	0.178	21.0	21.1
room5	11	○	○	○	○	○		○	○		0.187		129.8
	12		○		○	○		○	○		0.263		179.2
	13		○		○		○	○	○		0.263		179.5
	14		○		○		○	○			0.264		180.0
	15	○	○		○		○	○	○		0.207		144.8
	16		○		○		○	Ⅱ-G1			0.278		188.7
room6	17	○							○		0.093		52.5
	18	○						○	○		0.083		48.9
	19	○					○	○	○		0.032		35.5
	20	○	○	○		○		○	○		0.030		35.6
	21	○	○	○			○	○	○		0.034		36.4
	22	○	○	○					○		0.096		63.9
room7	23			○	○						0.204		32.4
	24	○	○	○	○						0.150		13.2
	25	○		○	○		○	○	○		0.188		35.9
	26			○	○	○		○	○		0.199		37.8
	27			○	○		○	○	○		0.200		38.1
	28			○	○		○	○			0.204		37.8
	29			○	○		○	Ⅱ-G1			0.205		38.9

We consider the second district. Table 6 shows the results of ventilation performance for a wind direction of 22.5°. Regarding the LDK, in case 1 where only the LDK south window was opened, the amount of ventilation is poor. However, opening the northern corridor window at the same time as in case 2 was effective, and in case 3, the effective ventilation frequency of the LDK reached a maximum. This is considered to be due to the influence of pollutants generated from the room when opening the window of the other room as the upstream side in the following cases. In case 6, in which all windows are opened, the total ventilation frequency was a maximum, but the average wind speed of the LDK and effective ventilation frequency were not optimal. Rather, the average wind speed increased in cases 7 and 8 where window 7-J, which is on the leeward side, was closed. In case 9, the average wind speed in the south became larger in case 10. This is thought to be due to the distribution of ventilation airflow to the south side of the LDK, which decreases because the ventilation that has flowed through the corridor changes greatly toward the eastern side when window II-H is opened. For room 5, the total ventilation frequency reached a maximum in case 11, but the average wind speed and effective ventilation frequency did not reach a maximum. The average wind speed and effective ventilation frequency were larger in cases 12 and 13 where the north windward opening was reduced. In this case, back flow occurred in all LDK south windows except II-GI and 6-I, and the average wind speed and effective ventilation frequency reached a maximum in case 16 in which this window was closed. With regard to room 6, in cases 18 and 19 in which the LDK leeward window was opened, and in case 17 as well, the average wind speed and effective ventilation frequency both decreased. In case 22, the average wind speed and effective ventilation frequency reached a maximum. This is considered to be due to the addition of the inflow opening as compared with case 17. Regarding room 7, the average wind speed and effective ventilation frequency were at a maximum in case 29. This is because we closed window 6-I other than window II-GI of the LDK South window where a reverse flow had occurred in case 28.

4 Conclusion

The following results were obtained from this research.

(1) The turbulence model used in the CFD in this study was the standard k-ε model incorporating the Durbin limiter, which had the best correspondence with the measured values.

(2) In Passive Town Kurobe, the WCs are not necessarily installed effectively in the first and second blocks.

(3) The basis for improving the ventilation performance is to fully open the window of the room targeted for ventilation, fully leave the window on the windward side if it is downwind, or leave the window on the windward side fully open if it is windward.

Two related articles are:

1. S. Komakine et al., A Study on Evaluation of Ventilation Performance in Passive Town Kurobe Model Based on Actual Measurement and CFD Summary of the Academic Proceedings of the Architectural Institute of Japan Journal of the Academy of Sciences (2017)
2. S. Komakine et al., Evaluation of ventilation performance in passive town Kurobe model based on actual measurement and CFD Aerospace and Sanitation Engineering Society Academic Lecture Collection Summary (2017)