Building simulation on utilization of roof window in detached house by using cross-ventilation

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Abstract
The effects of roof window on ventilation flow rates and reduction of cooling loads in densely populated areas were investigated by using building simulations. In May of the intermediate season, when utilizing roof window, the cumulative number of air exchanges increased by 9 % to 12 % compared to that when the windows at side walls remained open only during the daytime. When the building coverage ratio increased from 0 % to 20 %, the cumulative number of air exchanges decreased and the cumulative cooling loads increased. However, when the building coverage ratio increased from 20 % to 40 %, the cumulative number of air exchanges and cooling loads remained almost the same.

Keywords: roof window, cross-ventilation, building simulation, ventilation flow rate, cooling load, local dynamic similarity model(LDSM), COMIS, TRNSYS

Introduction

Cross ventilation is accepted as one of the effective energy conservation techniques. However, in densely built-up residential area such as Tokyo, it is not clear whether this approach can fully account for the beneficial effects with windows set on wall. It is believed that the influence of building coverage ratio on cross-ventilation could be improved by using roof void opening. Thus, there is a possibility that roof window plays an effective role for cross-ventilation in the area of high building coverage ratio. The objective of this study is to evaluate the advantage of roof window for cross-ventilation in the area of high building coverage ratio.

Simulation Outline

Simulation codes

The calculations of ventilation flow rate and cooling load for a detached house were performed by using a COMIS-LDSM model with a combination of TRNSYS thermal multizone building model. The Local Dynamic Similarity Model (LDSM) gives valuable information on inflow/outflow angles at openings[1]. The ventilation flow rates were calculated by the fundamental formulas (1) to (3) of the LDSM in Table 1. Fig.1 outlines the COMIS-LDSM model and the TRNSYS model[2, 3, 4]. The COMIS code was revised on the basis of LDSM model to calculate the discharge coefficients and airflow rates at inflow/outflow openings. Wind pressure (P_w), tangential dynamic pressure (P_t) and ventilation performances of inflow/outflow openings were provided as input data. Arbitrary room pressure (P_R) was given as an initial condition, and a discharge coefficient corresponding to P_R* was selected from the ventilation performance curve. The calculation was repeatedly conducted with different room pressures until ventilation flow rates of outflow and inflow in each room were balanced.

Residential house model

A typical residential house model[5] defined by the Architectural Institute of Japan was used as an object model. The residential house, cf. Fig.2 and Fig.5, has five rooms; a Living/Dining Room, a Kitchen and 3 bedrooms with a total floor area of 120 m^2, and it is assumed for a family comprising a couple with two children. It was also assumed that the building was insulated according to the next-generation energy saving standards. The residential house model was selected due to the results obtained from a survey by Nakamura et al. in 2000 for the special 23 wards of Tokyo[6]. The survey indicated that there were many two-story buildings which accounted for about 70 % of all buildings, and buildings of 100 m^2 or less for about 80 % of all buildings. The size of roof window is assumed 600mm×600mm. The ventilated space of the entire house is 229 m^3.

Meteorological conditions

The characteristics of meteorological factors in Tokyo were analyzed by using the extended AMeDAS weather data of the standard year. The analysis period was commenced in May including the intermediate season. The hourly mean temperature was recorded between 16.4 ℃ and 22.3 ℃. The relative humidity was 51 % to 73 %. When the wind speed was adjusted to that at the eaves height (5.9 m) of the detached house, the measured mean wind speed was between 1.3 m/s and 2.4 m/s. Southwest winds accounted for 20 % of the period when occupants were asleep, and south to southwest winds accounted for 50 % of the period when occupants were awake.

Building coverage ratios

In the survey done by Nakamura et al. in 2000, the gross building coverage ratio was found from 10 % to 50 % in the central part of Tokyo, and 90 % of that ranged from 15 % to 40 %. The building coverage ratios in this study were therefore set to 0 %, 20 % and 40 %. The wind pressure on an opening (P_w) and the tangential dynamic pressure (P_t) were obtained beforehand from a 1/100 scale model used in a wind tunnel experiment. Dummy models with identical configuration around the object model were arranged. The reference height was set at the eaves height of 5.9 m. The wind profile had a power index of 0.25 as shown in Fig.3. It was assumed that the ventilation performance of rectangular openings was in accordance with the results of Ohba et al. (2008), and the discharge coefficients of room doors were set to 0.63. The effects of adjacent building shadows that may reduce solar radiation loads in the house were, however not taken into account.

Outline of the simulation logic of window and air-conditioning operation

The decision tree of operation of cooling and windows is shown in Fig.4. Fig.5 shows the operation of opening and closing openings in the house[8]. The logic of opening/closing windows was applied to the windows and doors in the habitable rooms and the hall. Four cases were simulated as shown in Table 2. For Case 1, we only used the logic of turning on/off air-conditioners with all windows closed. For Case 2 and Case 3, the basic logic of opening/closing windows was used. Windows were opened in occupied rooms when the temperature exceeded 24 ℃ and closed when the temperature dropped below 23 ℃. Windows were closed when all family members either asleep or when the rooms were not occupied. For Case 4, the active logic of opening/closing windows was used. Even when residents were asleep, we opened the windows 20 % when the room temperature exceeded 24 ℃ and closed them when the temperature dropped below 23 ℃. Doors in habitable rooms were opened when the windows were opened and the doors were closed when the air-conditioners were turned on and/or the windows were closed.

The schedule of persons at home is shown in Table 3, proposed by AIJ. The same pattern was used during weekdays and weekends. It was assumed that the house was not occupied from 14:00-16:00 and the family was asleep from 23:00-6:00. It was also assumed that the Japanese room and the spare room were unoccupied all the time. According to the logics, the windows were opened and closed, and the air-conditioners were turned on and off at a 15-minute interval according to the temperature of each room.

Simulation results

Cumulative number of air exchanges in entire residential house

Fig.6 shows the cumulative number of air exchanges, which is defined as the number of time that the entire air volume in house changes with outside air. When the building coverage ratio was 0%, i.e. utilizing roof window in Case 3, the cumulative number of air exchanges increased by 9% compared to that of Case 2 when the windows remained open only during the daytime. If the windows remained 20% open and the duration of opening was kept longer, even during the time while occupants were asleep in Case 4, the cumulative number of air exchanges increased by 24 % compared to that of Case 2.

When the roof window was opened (Case 3) with a building coverage ratio of 20%, the cumulative number of air exchanges increased by 12% compared to that of Case 2. When the windows remained 20% open (Case 4), the cumulative number of air exchanges increased by 27 % compared to that of Case 2.

For the case with building coverage ratio of 40%, the cumulative number of air exchanges decreased compared with that when the building coverage ratio was 20%. When roof window was opened (Case 3), the cumulative number of air exchanges increased by 8% compared to that of Case 2. When the windows remained 20% open (Case 4), the cumulative number of air exchanges increased by 21 % compared to that of Case 2.

Cumulative hours of air-conditioner operation time in entire residential house

Fig.7 gives the cumulative air-conditioner operation time of the entire house. For the case of 0% building coverage ratio, it required 360 hours when the windows were closed (Case 1). The cumulative air-conditioner operation time reduced by 43% when the windows were kept open (Case 2). However, the effect of roof window in Case 3 was very small. When the windows remained 20% open (Case 4), it was reduced by 46%.

For the case of 20% building coverage ratio with the side windows remained open, the cumulative air-conditioner operation time was reduced by 42%. However, the effect of roof window (Case 3) was the same as that with a building coverage ratio of 0%. When the windows remained open 20% (Case 4), the cumulative air-conditioner operation time was reduced by 46%. However, when the building coverage ratio increased from 20 % to 40 %, the cumulative air-conditioner operation time remained almost the same as that with a building coverage ratio of 20%.

Cumulative cooling load in the entire residential house

As shown in Fig.8 and Table 4, with a building coverage ratio of 0%, the cumulative cooling load required 163 kWh when the windows remained closed (Case 1). When the side windows remained open (Case 2), the cumulative cooling load was reduced by 37 % compared to that of Case 1. The effect of roof window (Case 3) was not much significant, cf. Fig.7 and Fig.8. When the windows remained 20 % open (Case 4), the cumulative cooling load was reduced by 42 %.

For the case of 20% building coverage ratio with the side windows remained open, the cumulative cooling load was reduced by 28% compared to that of Case 1. When the windows remained 20 % open (Case 4), the cumulative cooling load was reduced by 38%. However, it remained almost the same even when the building coverage ratio increased from 20 % to 40 %.

Conclusions

We evaluated the effects of roof window on ventilation flow rates and reduction of cooling loads, according to different building coverage ratios by using the COMIS-LDSM model and the TRNSYS model.

- In May of the intermediate season, when utilizing roof window, the cumulative number of air exchanges increased by 9 % to 12 % compared to that when the side windows remained open only during the daytime.
- When the windows remained 20% open at night, the cumulative number of air exchanges increased by 21 % to 27 % compared to that when the windows remained open only during the daytime.
- The cumulative number of air exchanges decreased when the building coverage ratio increased from 0 % to 20 %. However, it remained almost the same even when the

building coverage ratio increased from 20 % to 40 %.

- The cumulative cooling load in the entire house, when the windows remained open in occupied rooms, was reduced by 28 % to 31 % compared to that when the windows remained closed completely. When the side and roof windows remained 20 % open at night, the cumulative cooling load was reduced by 36% to 40 % compared to that in Case 1.
- With a building coverage ratio of 20%, the reduction of cumulative cooling loads by roof window increased by 4% compared to that of the side windows.

Acknowledgments

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Nomenclature

A	opening area
C_d	discharge coefficient

C_{dS} basic discharge coefficient
Q ventilation flow rate
P_R room pressure
P_R* dimensionless room pressure
P_{RS}* dimensionless room pressure in case of $C_d = C_{dS}$
P_t dynamic pressure tangential to opening
P_W wind pressure
U_0 reference wind velocity at eave (=7m/s)
λ building coverage ratio
n power exponent
ρ air density
Z_m height of model
Z_p height of proto type

References

1. Kurabuchi T, Ohba M, Endo T, Akamine Y and Nakayama F., Local dynamic similarity of cross-ventilation, Part 1 Theoretical framework, *International Journal of Ventilation*, Vol.2, No 4, 2004, pp.371-382.

2. Ohba M., Tsukamoto T., Kurabuchi T., Goto T., Nonaka T. and Endo T., Study on energy conservation effects of wind-induced ventilation in detached house using coupled simulation of semi-empirical ventilation model and network models, *Proceedings of 29th AIVC Conference*, Vol.3, 2008, pp.21-26.

3. Ohba M., Kurabuchi T., Tsukamoto K., Nonaka T. and Goto T., A simulation study on the reduction of cooling loads in a detached house by cross-ventilation using the local dynamic similarity model, *The International Journal of Ventilation*, Vol.8, No 3, 2009, pp.251-264.

4. Tsukamoto K., Ohba M., Kurabuchi T., Nonaka T. and Goto T., Study on reduction of cooling loads in detached house by cross-ventilation using coupled simulation of semi-empirical ventilation model and network models, Proceeding of the 11th International Conference on Air Distribution in Rooms, Korea, 2009, pp.1541-1548

5. Udagawa H., Typical problems for house, 15^{th} Heat Symposium, AIJ, 1985, pp.49-56 (in Japanese).

6. Nakamura O., Miyashita K., Uematsu Y. and Yamada M., Actual conditions of terrain roughness evaluated from numerical data of structural dimensions in Tokyo, Journal of Wind Engineering, No 84, 2000, pp.59-69 (in Japanese).

7. Architectural Institute of Japan, Expanded AMeDAS weather data, Tokyo, Maruzen, 2003.

8. Nagai T., Windows and HVAC operation to reduce cooling requirement by means of cross-ventilation, International Journal of Ventilation, Vol.5, No 1, 2006, pp.151-162.

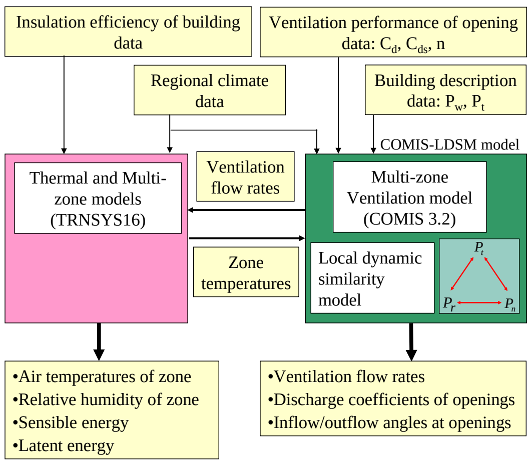


Fig. 1 Block diagram of COMIS-LDSM & TRNSYS model

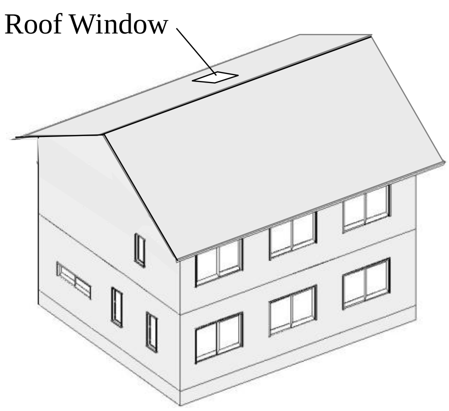


Fig. 2 AIJ residential house model

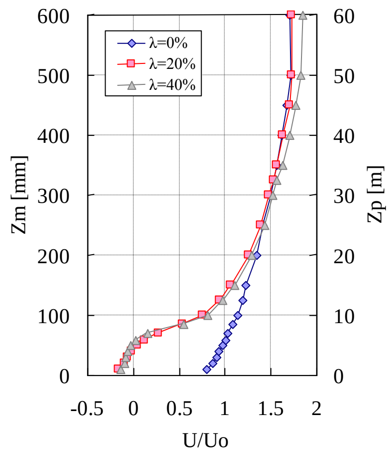
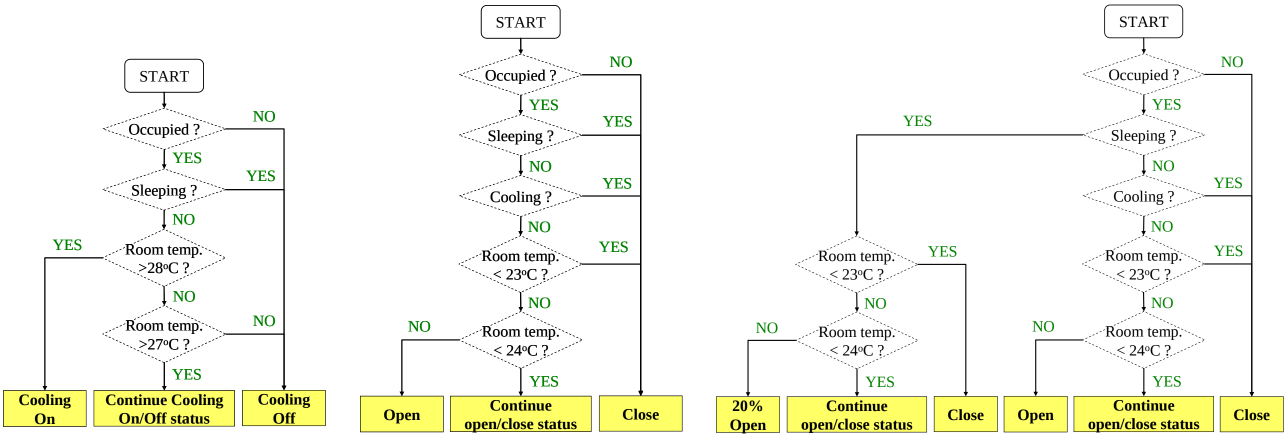
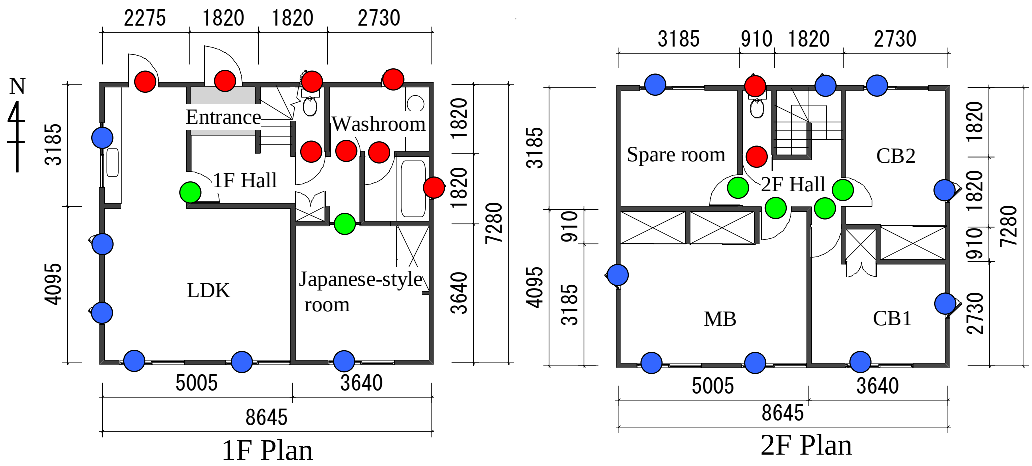


Fig. 3 Wind profile in wind tunnel experiments



(1) Cooling (2) Basic Window (3) Active Window

Fig. 4 Operation of cooling and window



※ 🔵 : Setting the logics of opening/closing windows and turning on/off air conditioning

※ 🟢 : Opening doors only when windows are opened

※ 🔴 : Windows and doors remained closed all the time

Fig. 5 Location of opening/closing windows

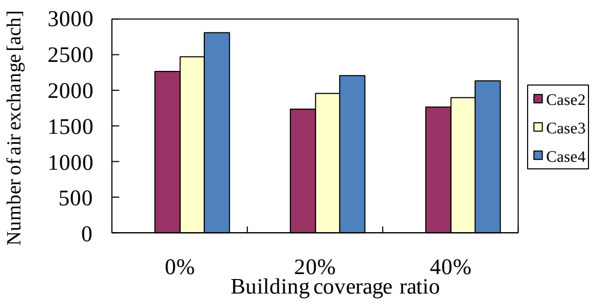


Fig. 6 Cumulative number of air exchanges

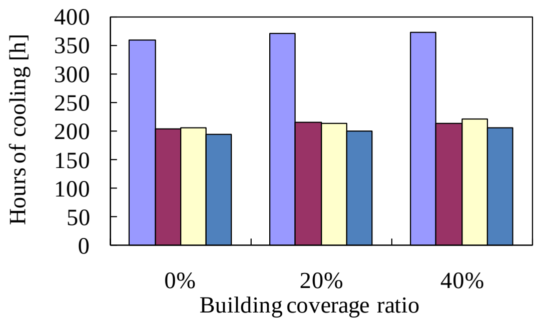


Fig. 7 Cumulative operating hours of air-conditioners

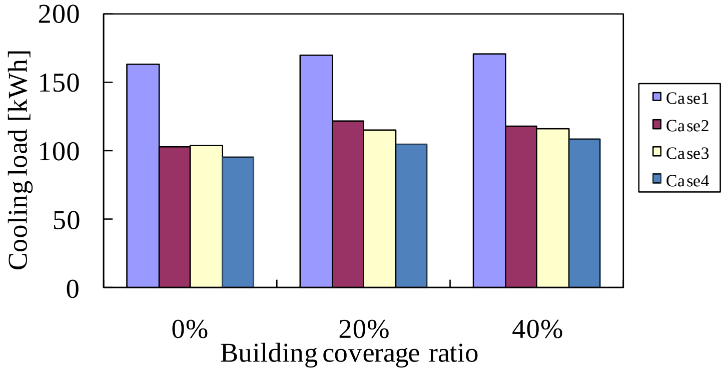


Fig. 8 Cumulative cooling loads

Table 1 Fundamental formulas of local dynamic similarity model

$$P_R^* = \frac{P_R - P_W}{P_t} \qquad (1) \qquad Q = C_d A \sqrt{\frac{2}{\rho}\left|P_R - P_W\right|} \qquad (2) \qquad C_d = C_{d\,S}\left(\frac{P_R\,*}{P_{RS}\,*}\right)^n \qquad (3)$$

Table 2 Simulation cases on reduction of cooling loads by cross-ventilation

Case	Air-conditioner operation	Window operation	Window type
1	On/Off	All windows closed	Side windows
2	On/Off	Basic logic of windows Opened/Closed	Side windows
3	On/Off	Basic logic of windows Opened/Closed	Side & roof windows
4	On/Off	Active logic of windows Opened/Closed	Side & roof windows

Table 3 Schedule of occupied time zone

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
LDK	0	0	0	0	0	0	1	4	1	1	1	1	1	1	0	0	3	3	3	3	2	2	1	0
MB	2	2	2	2	2	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2
CB1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
CB2	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1

Table 4 Cooling load reduction ratios of the entire house with each building coverage ratio

Case	λ=0% [kWh]	λ=20% [kWh]	λ=40% [kWh]
Case1	63 (-)	170 (-)	170 (-)
Case2	102 (37.3%)	122 (28.1%)	118 (30.7%)
Case3	103 (36.8%)	115 (32.4%)	116 (32.1%)
Case4	96 (41.5%)	104 (38.4%)	108 (36.3%)