A Simulation Study on the Reduction of Cooling Loads in a Detached House by Cross-Ventilation using the Local Dynamic Similarity Model

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Abstract

A simulation study on the reduction of cooling loads by utilizing cross-ventilation was performed for a typically shaped house as defined by the Architectural Institute of Japan. A reduction in cooling load of around 50% could be achieved when the windows were opened liberally at night compared with the cooling load when all the windows remained closed, regardless of building coverage ratio.

Key words: Local Dynamic Similarity model, cross-ventilation, COMIS, TRNSYS, detached house, cooling load, ventilation path, energy saving.

1. Introduction

Increasing social consciousness of environmental protection and energy saving has given rise to a demand for natural energy utilization in buildings and houses. Various technologies have been studied for natural energy utilization, and, of these, cross-ventilation has lately attracted considerable attention. However, many researchers have demonstrated problems that debase the prediction accuracy of the network model. One of the main problems is that discharge coefficients, which relate wind pressures to ventilation flow rates, vary with wind direction and opening position although they are treated as constants in the conventional model (Karakatsanis, 1987).

To solve this problem, the authors proposed an empirical model based on the results of research on CFD analysis and of wind tunnel experiments (Kurabuchi et al., 2004). This model, called a Local Dynamic Similarity Model (LDSM), expresses the variation of discharge coefficient with wind direction, and thus predicts ventilation flow rates more accurately than the conventional method (Ohba et al., 2004).

This paper describes the newly developed COMIS-LDSM model where COMIS is used as a network model for ventilation simulation (Ohba et al., 2008). The effects of reducing cooling loads through cross-ventilation of a detached house were evaluated by coupled simulation on the COMIS-LDSM and a thermal and multi-zone model (TRNSYS).

2. Outline of COMIS-LDSM Model

2.1 Local Dynamic Similarity Model (LDSM)

Figure 1 shows the pressures in the vicinity of an inflow opening. It is possible to consider that the pressure field at the inflow opening is represented by three pressures: dynamic pressure normal to the opening (P_n), dynamic pressure tangential to the opening (P_t) and ventilation driving pressure (P_r). Thus, total pressure P_T at an inflow opening is

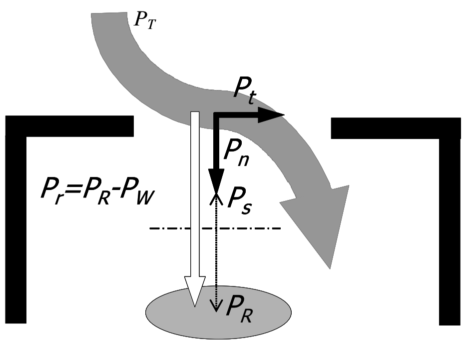


Figure 1. Dynamic similarity in vicinity of inflow opening.

Table 1. Fundamental formulas of local dynamic similarity model.

$P_R^* = \dfrac{P_r}{P_t}$	(1)
$C_d = \sqrt{\dfrac{P_n}{\lvert P_r \rvert}}$	(2)
$\beta = \tan^{-1}\sqrt{\dfrac{P_t}{P_n}}$	(3)
$P_r = P_R - P_W$	(4)
$Q = C_d A \sqrt{\dfrac{2}{\rho}\lvert P_r \rvert}$	(5)
$C_d = C_{dS}\left(\dfrac{P_R^*}{P_{RS}^*}\right)^n \quad \left(\lvert P_R^* \rvert \le \lvert P_{RS}^* \rvert\right)$	(6)
$C_d = C_{ds} \quad \left(\lvert P_R^* \rvert \ge \lvert P_{RS}^* \rvert\right)$	(7)

$P_n+P_t+P_S$. The LDSM model assumes that P_n, which is directly related to the ventilation flow rate (Q), is uniquely determined by P_t and P_r, and that there are dynamic similarities in the relationships among the three pressures when the ratios of P_r to P_t are coincident. Kurabuchi and Ohba et al. (2004) defined the ratio of P_r to P_t as dimensionless room pressure (P_R*) by Equation (1), as shown in Table 1. The discharge coefficient (C_d) and the inflow angle (β) are described by the ratios of P_n to P_r and P_t to P_n, which are given by Equation (2) and Equation (3), respectively. The characteristics of ventilation performance through an opening can be represented by Equations (6) and (7), as shown in Figure 2. Appropriate discharge coefficients can be calculated from Equations (1) to (7) even when wind direction angles and opening locations are different (Ohba et al., 2006).

2.2 COMIS-LDSM

The LDSM model was coupled with the COMIS code as shown in Figure 3 (Ohba et al., 2008a). This code is widely used as a multi-zone ventilation model for ventilation simulation. P_W and P_t for the building envelope are provided as input data. The ventilation performance of inflow and outflow openings is also provided as input data. Based on the LDSM model, the COMIS code was revised to calculate the discharge coefficients and airflow rates at inflow/outflow openings. Arbitrary room pressure (P_R) is given as an initial condition and a discharge coefficient corresponding to P_R* is selected from the ventilation performance curve. The calculation was performed by the Relaxation-Newton method until ventilation flow rates of outflow and inflow in each room were balanced.

The coupled model can estimate ventilation flow rates more accurately than the conventional orifice model because it can select discharge coefficients suitable for arbitrary wind directions when the wind direction is not normal to the openings. It can also determine the inflow/outflow angles at the openings from Equation (3), which provides us with important information on the internal flow patterns.

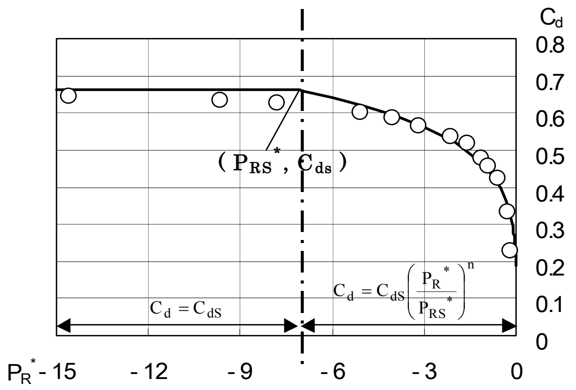


Figure 2. Ventilation performance expression for basic inflow opening.

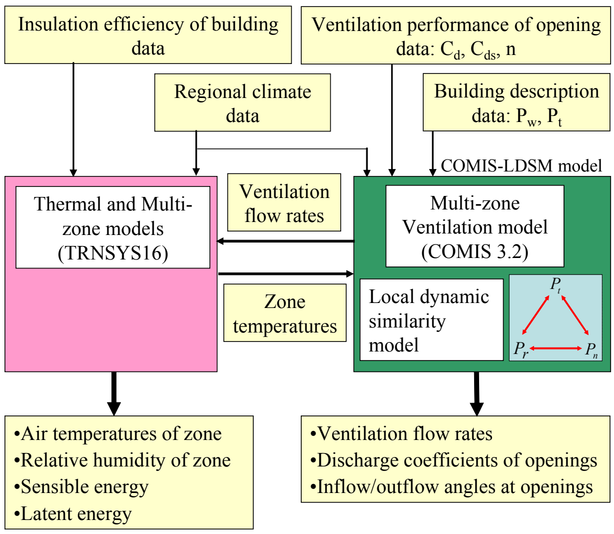


Figure 3. Block diagram of COMIS-LDSM and TRNSYS model.

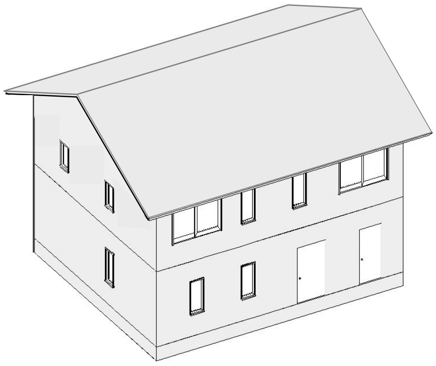


Figure 4. AIJ detached house model.

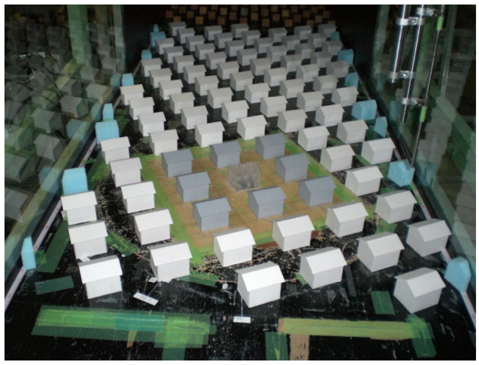


Figure 5. Layout of detached houses for gross coverage ratio of 20%.

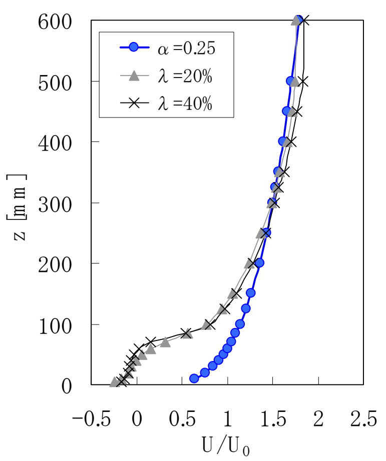


Figure 6. Vertical profile of approaching flow.

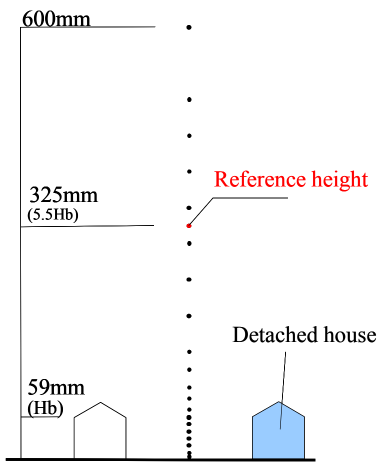
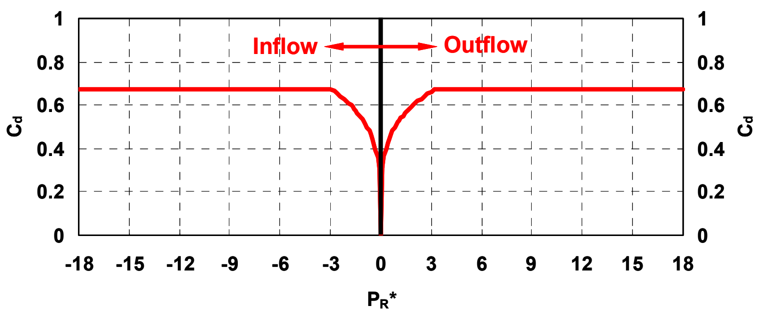


Figure 7. Measuring location of reference velocity.



Location of opening	C_{ds}	P_{RS}*	n
Inflow	0.67	-0.29	0.23
Outflow	0.67	3.17	0.22

Figure 8. Ventilation performance expressions for inflow and outflow openings.

3. Input Database of Building for Application of the COMIS-LDSM Model

Building information on wind pressure P_w and tangential dynamic pressure P_t and ventilation performance of openings are required when the COMIS-LDSM model is applied to the case study on ventilation flow rates. P_w and P_t of the wall openings and roof window were obtained beforehand from a 1/100 scale model through a wind tunnel experiment.

3.1 Detached House Model

A typically shaped house was defined by the Architectural Institute of Japan (AIJ), as shown in Figure 4. The family in the studied house was assumed to be composed of four persons: two children, a daily commuter and a homemaker. It had 2 storeys and a total floor area of 120 m^2, comprising six rooms including a living room and kitchen. The eaves height was 5.4 m. It was insulated according to next-generation energy standards.

3.2 Experimental Conditions and Measuring Procedures

The model scale was 1:100 in the wind tunnel experiment. In assuming the urban area, some dummy models were placed in a region from 2 m upwind to 0.5 m downwind of the target model, as shown in Figure 5. The building coverage ratios were set to 0%, 20% and 40%. The velocity profiles of the approaching flows are shown in Figure 6. The velocity at the eaves of the target model could not be measured due to the surrounding dummy models, so the reference point was set at a height of 5.5 H_b as shown in Figure 7. The reference velocity was determined by the profile with a power-law index of 0.25 to maintain 7.0 m/s at the upwind eave of the model.

Wind pressure distributions at the model surface were collected by a multi-point manometer. Irwin's surface wind sensor (Irwin, 1981) was used to measure P_t. The details of this method were previously reported (Kurabuchi et al., 2005). P_t was calculated from the relationship between the pressure of Irwin's sensor and the tangential wind velocity at the target opening. The tangential wind velocities U_t at 3.75 mm from the wall and roof surfaces were measured by a split-film anemometer. The measuring height was equivalent to one fourth of the average opening height. The P_t distribution on the wall and roof surface of the detached house model for an arbitrary wind angle was obtained from the calibration data.

3.3 Ventilation Performance of Openings

The ventilation performance of inflow/outflow openings and roof opening was obtained from Figure 8 as input data (Ohba et al., 2004; Kurabuchi et al., 2005). The C_d of the internal doors was set to a constant value of 0.63 for the present calculation.

4. Comparison between Predicted Ventilation Flow Rates of COMIS-LDSM Model and Conventional Model

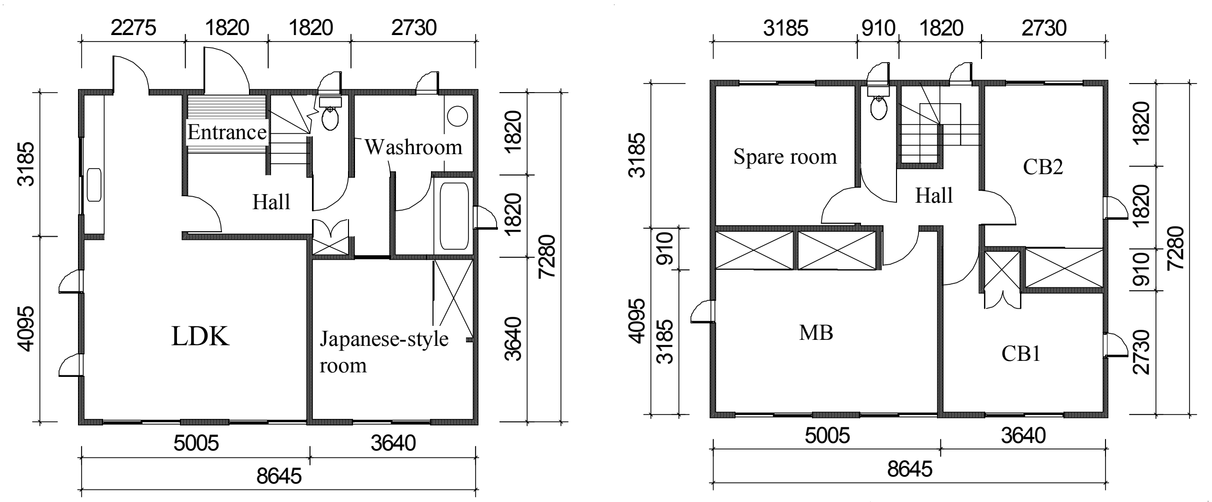
4.1 Simulation Outline

Figure 9 shows a floor plan of the detached house model. All windows and internal doors in rooms other than toilets and bathrooms are kept open. The inside and outside temperature is set to 20 °C, assuming that there is no buoyancy-driven ventilation. The reference velocity at the eaves height is kept at 1.0 m/s (Ohba et al., 2008b).

4.2 Simulation Results

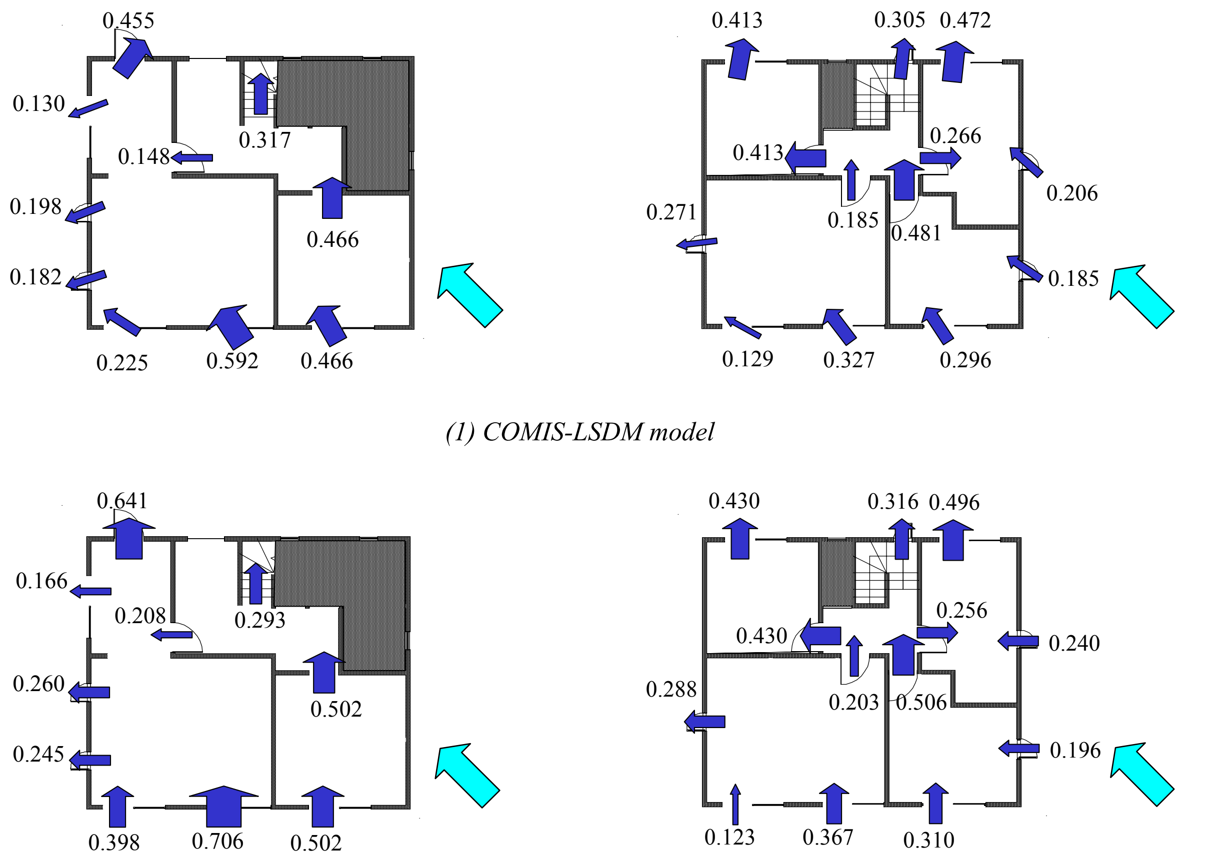
Figure 10 shows the inflow/outflow incident angles and ventilation flow rates in rooms for a wind angle of 135°. The building coverage ratio is 0%. The Q value for the conventional orifice model was calculated in the conventional way (C_d fixed). The COMIS-LDSM can provide us with more useful information when predicting internal flow patterns. The incident angles at the corner openings in the LDK and bedrooms on the 2nd floor were larger than those at other upwind openings of the LDK and bedroom due to the airflow passage along the external wall surface.

Figure 11 shows the calculated ventilation flow rates in rooms for a wind angle of 135°. There was a 26% difference between the airflow rates of the conventional orifice model and COMIS-LDSM in the LDK. In the other rooms it was 5-9%. Figure 12 shows the total ventilation flow rates in the house for each wind angle. The conventional orifice model overestimated the ventilation flow rates compared to those obtained from the COMOS-LDSM for wind angles of 45°, 135° and 315°, especially where the approaching flow was not normal to the upwind openings. This may cause poor prediction of cooling load reduction when utilizing cross-ventilation for saving energy consumption of the air-conditioning system.



1^{st} *floor plan* 2^{nd} *floor plan*

Figure 9. Floor plan of detached house model.



(2) Orifice model *[Dimensions in m^3/s]*

Figure 10. Calculated ventilation flow rates for wind angle of 135° and building coverage ratio of 0% when using COMIS-LDSM model and conventional Orifice model.

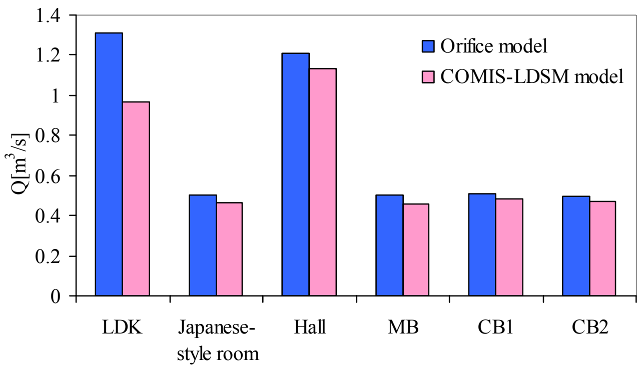


Figure 11. Calculated ventilation flow rates in rooms for wind angle of 135°.

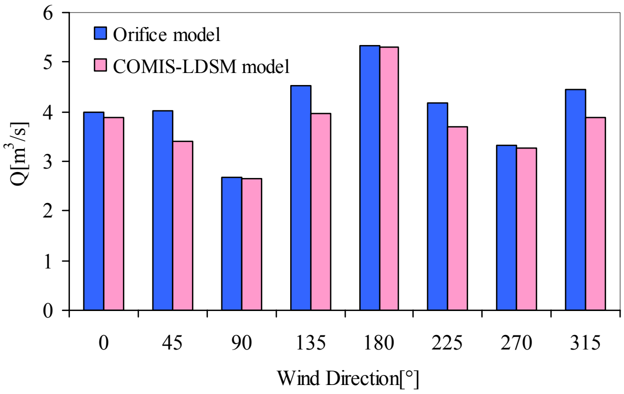
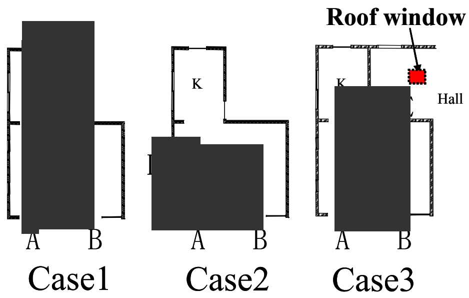


Figure 12. Calculated total ventilation flow rates in the house for each wind angle.



Opening	Area[m^2]
A,B	1.70
C	1.60
D	0.60
E	0.36

Figure 13. Route of cross-ventilation path and opening area.

5. Simulation Study on Effective Ventilation Path in a Densely Populated Urban Area

5.1 Simulation Outline

Figure 13 shows the layout of window openings. The target windows are located at A - D in the LDK and at E in the roof above the hall. The window openings in the other rooms were assumed to be closed. The other calculation conditions are the same as in the previous section.

5.2 Simulation Results

For a building coverage ratio of 0% (see Figure 14), the airflow path for Case 1 with face-to-face-type openings showed the largest Q values of the three cases. However, when the approaching flow moved tangentially along these openings, the ventilation flow rate greatly decreased. For a building coverage ratio of 20%, as shown in Figure 15, the airflow path of Case 1 still showed a larger change of Q values for all wind directions. The airflow paths of

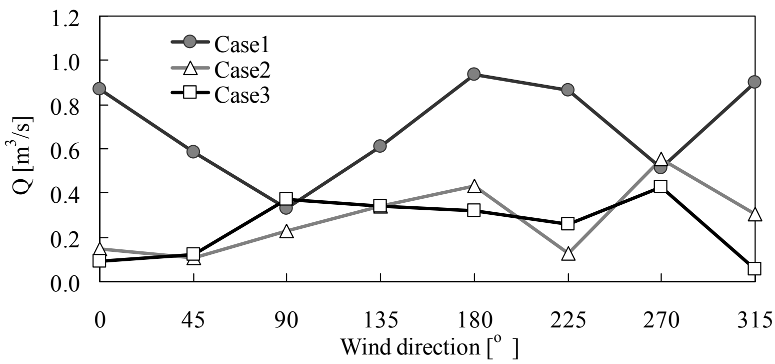


Figure 14. Ventilation flow rates for gross coverage ratio of 0%.

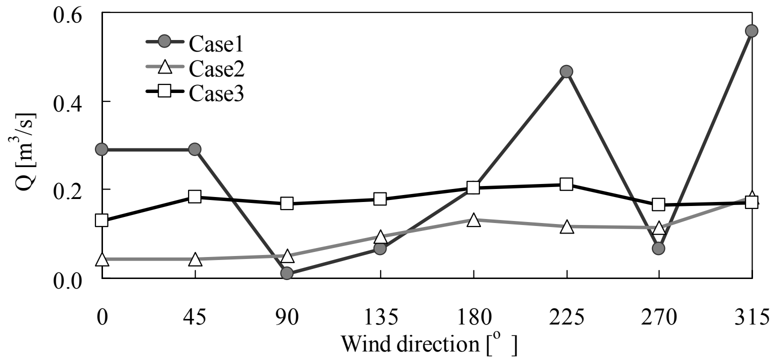


Figure 15. Ventilation flow rates for gross coverage ratio of 20%.

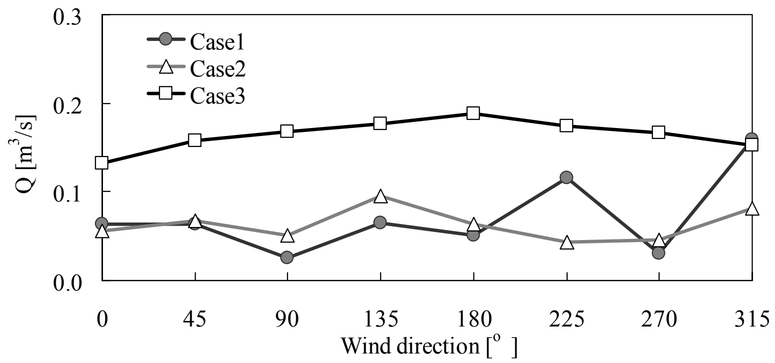


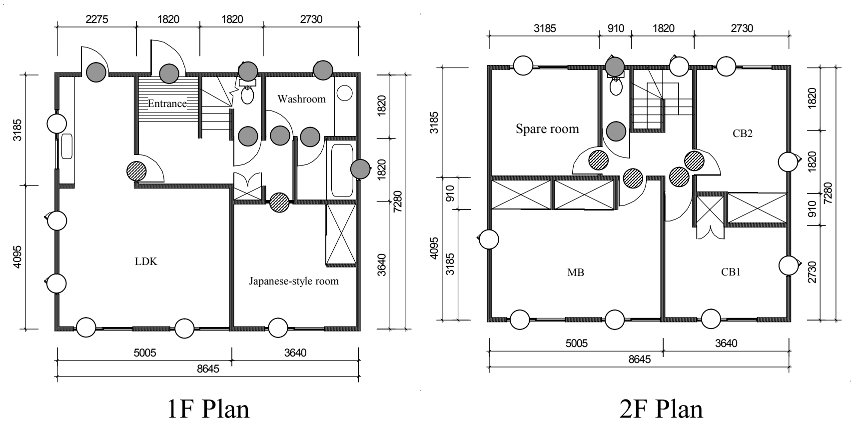
Figure 16. Ventilation flow rates for gross coverage ratio of 40%.

Case 2 with corner-type opening and Case 3 with roof-window-type openings, on the other hand, did not show large differences in Q values with change in wind direction. For a building coverage ratio of 40%, as shown in Figure 16, the roof-window-type opening showed larger Q values and constant ventilation flow rates regardless of wind direction. The roof window was found to be more effective for obtaining good ventilation flow rates in densely populated urban areas than wall window openings.

6. Simulation Study on Reduction of Cooling Loads by Cross-Ventilation

6.1 Simulation Outline

The simulation study was also performed for the AIJ detached house model to calculate the cooling load reduction effect when utilizing cross-ventilation. Windows in habitable rooms and halls, and room doors were opened and closed according to the logic



※ ○ :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

Figure 17. Location of opening/closing windows.

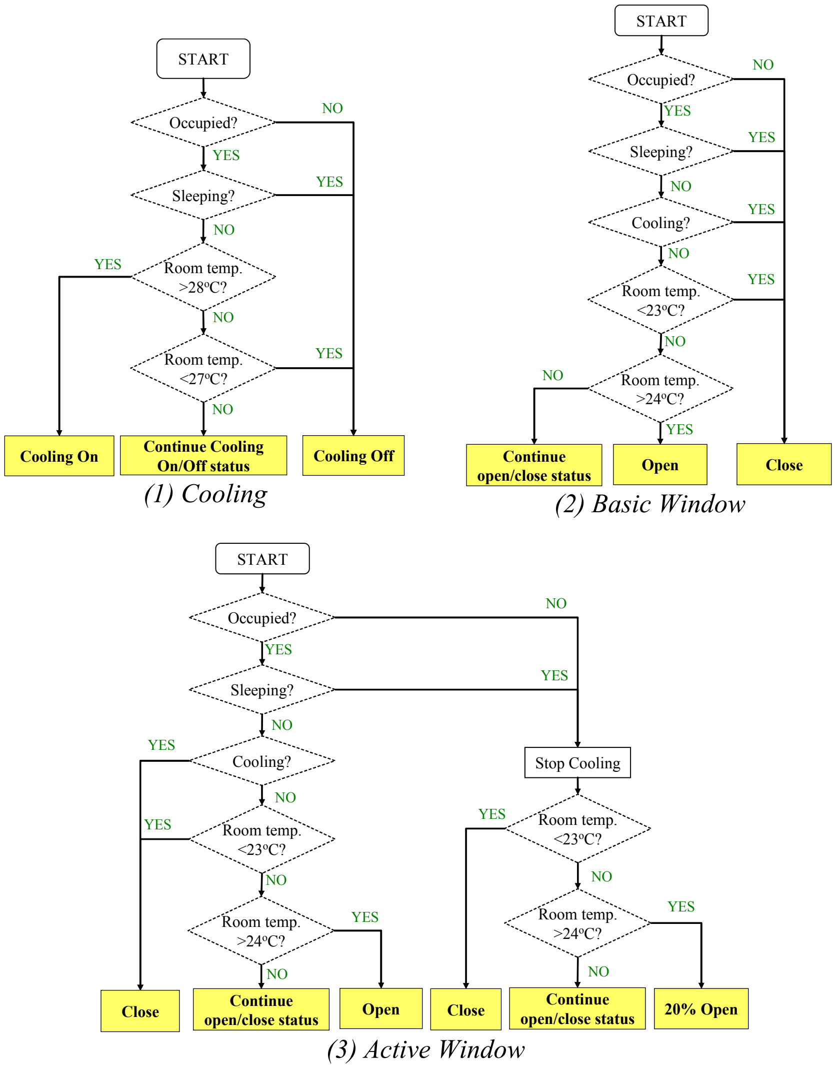


Figure 18. Logic of operation of cooling and windows.

of opening/closing windows and the logic of turning on/off air-conditioners (see section 6.2 below). Windows and doors in the toilets, bathroom and washrooms were kept closed, as shown in Figure 17. Expanded AMEDAS weather data were used for the meteorological data in Tokyo and the period was set to the month of June. The ventilation performance of the outside windows was as shown in Figure 8. The discharge coefficients of the room doors were set to 0.63.

6.2 Logic of Opening/Closing Windows and Turning On/Off Air-Conditioners

The decision tree for the operation of cooling and windows is shown in Figure 18 (Nagai et al., 2006; Tsukamoto et al., 2009). The logic of turning on/off air-conditioners was applied only to the LDK, the master bedroom and the two children's rooms. Air-conditioners were not used in the other rooms. When the room temperature exceeded 28 °C in an occupied room, the air-conditioner was turned on and when the room temperature dropped below 27 °C, the air-conditioner was turned off. The cooling temperature controlled by the air-conditioners was set to 28 °C and the humidity to 60%. The logic of opening/closing windows was applied to the windows and doors in the habitable rooms and the hall.

Three 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, the basic logic of opening/closing windows was used. Windows were opened in occupied rooms when the temperature exceeded 24 °C and closed when the temperature dropped below 23 °C. Windows were closed when all family members would be sleeping or when rooms were not occupied. For Case 3, the active logic of opening/closing windows was used. When the house was occupied (even when residents were asleep or the rooms were not occupied), we opened the windows 20% when the room temperature exceeded 24 °C and closed them when the temperature dropped below 23 °C. Doors in habitable rooms were opened when the windows were opened and the doors were closed when the air-conditioners were on and/or the windows were closed.

The schedule of persons at home was followed according to Table 3 proposed by AIJ (Udagawa, 1985). The same pattern was used during weekdays and weekends. It was assumed that the house was unoccupied from 14:00-16:00 and the family was asleep from 23:00-6:00. It was also assumed that the Japanese room and a spare room were unoccupied all the time. Simulation was carried out every 15 minutes to evaluate window status and air-conditioner operation.

6.3 Simulation Results for Room Temperatures in LDK for a Single Day

Figure 19 shows room window operation, air-conditioner operation and room temperature in the LDK for a gross coverage ratio of 0%. The average meteorological data of June 18 were used. In Case 1, where the doors were closed routinely, air-conditioners were turned on when the rooms were occupied from 6:00-14:00 and from 16:00-23:00. The temperature rose to 30°C from 14:00-16:00

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

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

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

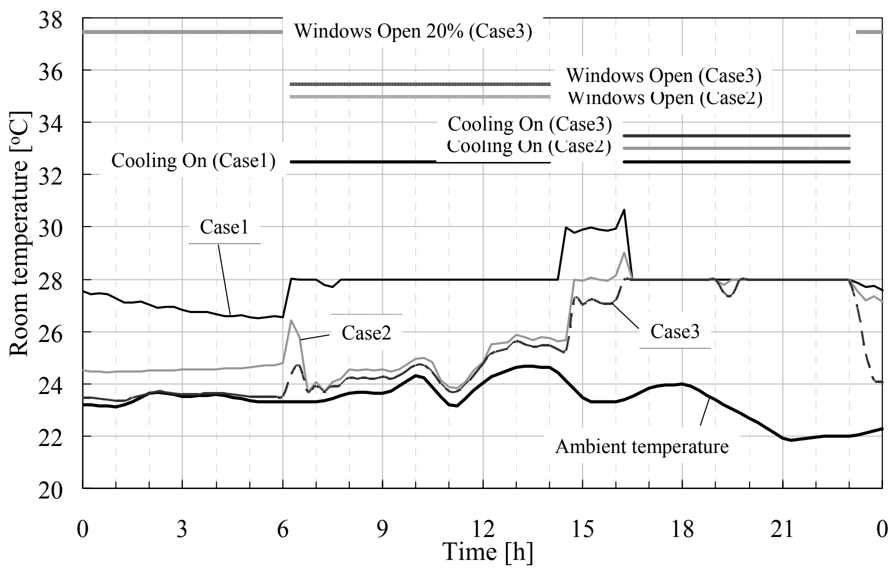


Figure 19. Time-history of room temperatures in LDK for a day for gross coverage ratio of 0%.

during the unoccupied period. The room temperature exceeded 26 °C even while residents were sleeping. The room temperature was 4 °C to 6 °C higher than the outside temperature and the fluctuation of room temperature was minor throughout the day.

In Case 2, the windows were opened from 6:00-14:00 and the room temperature tended to be slightly higher than the outside temperature. Because the windows were closed from 23:00-6:00, room temperature was 2 °C to 5 °C higher than the outside temperature.

In Case 3, the windows were closed from 6:00-14:00 and room temperature showed almost the same tendency as the outside temperature. Because the windows were opened 20% even while residents were asleep from 23:00-6:00, changes in room temperature had the same tendency as the outside temperature. The room temperature in Case 3 was 3 °C to 4 °C lower than in Case 1 and 2 °C lower than in Case 2 except when the air-conditioners were turned on, so the operating time of the air-conditioners could be reduced.

Figure 20 shows room window operation, air-conditioner operation and room temperature in the LDK for a gross coverage ratio of 20%. In Case 2, the windows were closed from 6:00-14:00 and room temperature showed almost the same tendency as in Case 1. The room temperature from 0:00-6:00 was a little lower than that in Case 1 because the air-conditioner was turned on. The room temperature in Case 3 was slightly higher than the outside temperature. However, the difference of building coverage ratios did not have much effect on room temperature variation.

6.4 Simulation Results for Cumulative Hours of Cooling and Windows Remaining Open in LDK for the Month of June

Figures 21 and 22 compare the cumulative times the windows remained open in June for building coverage ratios of 0% and 20%, respectively. For the building coverage ratio of 0%, the cumulative time the windows remained fully open was longest in the LDK, and shortest in the master bedroom in both Case 2 and Case 3. However, if the length of time the windows remained 20% open is included, the length of time windows remained open in the master bedroom and the children's rooms exceeded 350 hours in Case 3, over 120 hours longer than in the LDK. Opening the windows 20% greatly helped the utilization of cross-ventilation.

For the building coverage ratio of 20%, the length of time windows remained open in the LDK was 16 hours shorter than for the building coverage ratio of 0%. With increasing building coverage ratio, the length of time windows remained open tended to decrease. However, when the windows were opened liberally at night, the effect of building coverage ratio on the length of time windows remained open decreased.

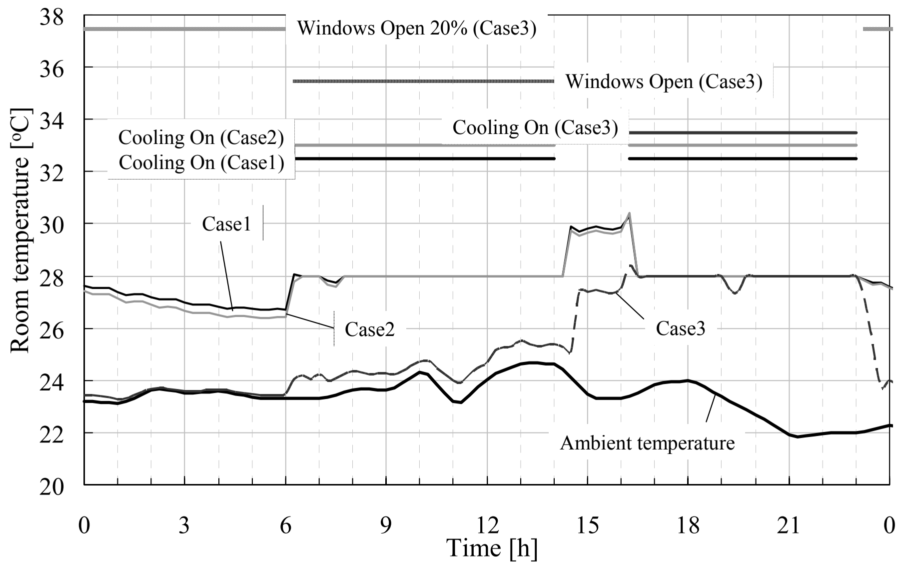


Figure 20. Time-history of room temperatures in LDK for a day for gross coverage ratio of 20%.

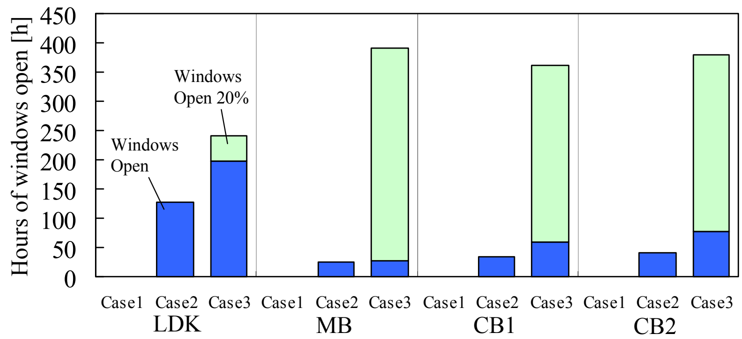


Figure 21. Cumulative hours of windows remained open in June for gross coverage ratio of 0%.

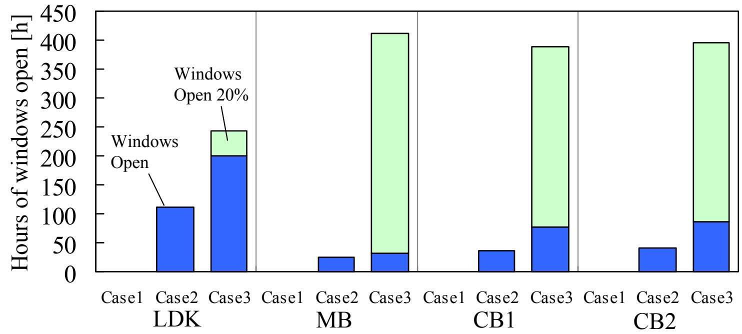


Figure 22. Cumulative hours of windows remained open in June for gross coverage ratio of 20%.

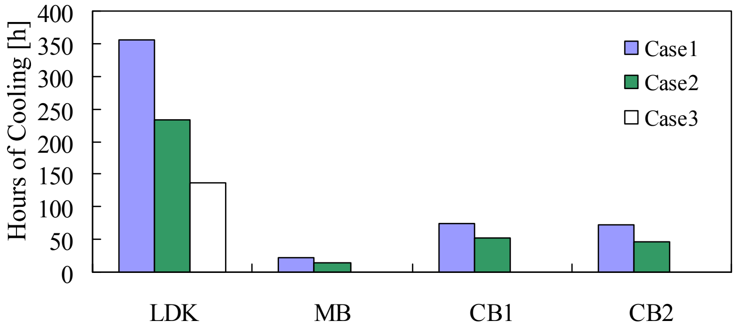


Figure 23. Cumulative operating hours of air-conditioners in June for gross coverage ratio of 0%.

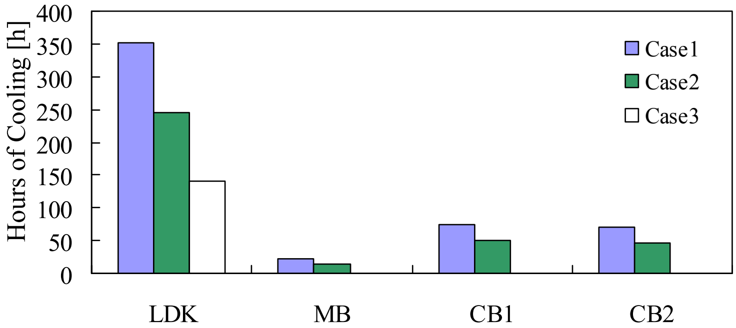


Figure 24. Cumulative operating hours of air-conditioners in June for gross coverage ratio of 20%.

Figures 23 and 24 compare the air-conditioner operating times for building coverage ratios of 0% and 20%, respectively. As shown in Figure 23, a reduction in air-conditioner operating time of 123 hours for the LDK and of 8 to 26 hours for the other habitable rooms was achieved by opening the windows during the occupied time zone. In Case 3, where the windows were opened liberally at night, a further reduction of 95 hours was achieved in the LDK and the air-conditioners did not need to be operated in the other habitable rooms at all. For the building coverage ratio of 20%, the operating time of the air-conditioners in the LDK increased by over 12 hours. With increasing building coverage ratio, the operating time of the air-conditioners tended to increase. However, when the windows were opened liberally at night, the effect of building coverage ratios decreased.

6.5 Simulation Results for Cumulative Cooling Loads in LDK for the Month of June

Tables 4, 5 and 6 show the cumulative cooling loads in June and the effects of reducing energy through cross-ventilation in Cases 1, 2 and 3 for each building coverage ratio. For the building coverage ratio of 0%, utilization of cross-ventilation succeeded in reducing cooling loads by 45 KW (17%) compared to those required when the windows were closed. In addition, when the windows also remained open during the unoccupied time zone or while residents were sleeping, the cooling load was 152 KW less than that required when the windows remained closed. It was 99 KW less than the cooling load required when the windows remained open in the occupied rooms. The cooling load was reduced by 58% compared to that when all windows remained closed. For the building coverage ratio of 20%, utilization of cross-ventilation succeeded in reducing cooling loads by only 5% compared to those required when the windows were closed. However, when the windows remained open during the unoccupied time zone or while residents were sleeping, the cooling load was reduced by 51% compared to that when all windows remained closed. With increasing building coverage ratio, the velocities around houses decreased so that the cooling loads increased by 12%-17% compared with that of basic window operation in Case 2. However, when the windows were opened liberally at night, the reduction in cooling loads was by about 50% regardless of building coverage ratio.

Table 4. Cumulative cooling load and reduction of cooling load in June for gross coverage ratio of 0%.

Case	Window operation	Cumulative Cooling load [KW]	Reduction of cooling load [%]
1	Closed	264	—
2	Basic Opened/Closed	219	17.0
3	Active Opened/Closed	112	57.8

Table 5. Cumulative cooling load and reduction of cooling load in June for gross coverage ratio of 20%.

Case	Window operation	Cumulative Cooling load [KW]	Reduction of cooling load [%]
1	Closed	261	—
2	Basic Opened/Closed	247	5.1
3	Active Opened/Closed	120	51.4

Table 6. Cumulative cooling load and reduction of cooling load in June for gross coverage ratio of 40%.

Case	Window operation	Cumulative Cooling load [KW]	Reduction of cooling load [%]
1	Closed	260	—
2	Basic Opened/Closed	257	0.9
3	Active Opened/Closed	126	51.4

7. Conclusions

Based on a reviewing of our previous research results and newly performed simulation study, the reduction of cooling loads by utilization of cross-ventilation was discussed and the following results were achieved:

- The conventional orifice model tended to overestimate the ventilation flow rates compared to those by the COMOS-LDSM especially when the approaching flow was not normal to the upwind openings because the discharge coefficients of openings were assumed to be kept constant regardless of wind directions.

- The roof window was found to be very effective for achieving constant ventilation flow rates in densely populated urban areas, regardless of wind direction.

- A reduction in cooling load of around 50% could be achieved when the windows were opened liberally at night compared with the cooling load when all the windows remained closed, regardless of building coverage ratio.

Acknowledgement

This study was partially funded by the Ministry of Education, Culture, Sports, Science and Technology, Japan, through the Global Centre of Excellence Program of Tokyo Polytechnic University.

Nomenclature

A opening area
C_d discharge coefficient
C_{dS} basic discharge coefficient
H_b eave height of detached house model
Q ventilation flow rate
P_n dynamic pressure normal to opening
P_0 dynamic pressure of reference velocity ($=\rho U_0^2/2$)
P_R room pressure
P_r ventilation driving pressure ($=P_R-P_W$)
P_R* dimensionless room pressure
P_{RS}* dimensionless room pressure in case of $C_d = C_{dS}$
P_S static pressure at opening
P_t dynamic pressure tangential to opening
P_T total pressure
P_W wind pressure
U_0 reference wind velocity at eave (=7m/s)
λ building coverage ratio
α power exponent
β inflow/outflow angle
ρ air density

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