Study on energy conservation effects of wind-induced ventilation in detached house using coupled simulation of semi-empirical ventilation model and network models

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ABSTRACT

A semi-empirical ventilation model was proposed for cross-ventilation. This model is based on local dynamic similarity theory and was coupled with COMIS and TRNSYS, which are widely used for energy conservation simulation. A simulation study was performed on a typical detached house in Japan to evaluate the energy conservation effect of cross-ventilation during the day. The conventional Orifice model overestimated the ventilation flow rates compared to those by COMIS-LDSM, especially when the approaching flow was not normal to the upwind openings. It tended to overestimate energy reduction loads when cross-ventilation was utilized.

1. INTRODUCTION

In recent years, there has been a lot of interest and concern about the utilization of air flow for improving indoor conditions in hot and humid rooms, which is important for energy-saving in buildings. Attempts have been made to effectively utilize natural ventilation, particularly in commercial buildings. To expand the use of natural ventilation, it is important to establish a high-precision model for predicting ventilation flow rate as a basic technique.

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 while they are fixed as constants in the conventional Orifice model (Vickery at al. 1987). In order to solve this problem, Kurabuchi and Ohba et al. (2004) developed a semi-empirical ventilation model, called a local dynamic similarity model, that explains the variation of discharge coefficients, and validated it for inflow and outflow openings.

This paper reports a simulation study on energy conservation effects of wind-induced ventilation in a detached house using coupled simulation of a semi-empirical ventilation model and network models.

2. COUPLED MODEL OF COMIS- LDSM

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). The local dynamic similarity model assumes that P_n, which is directly related to 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, as shown in Figure 2. 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, respectively. If the above assumptions are true, these are uniquely determined by the ratios of P_r to P_t.

The fitted curve of ventilation performance for an inflow opening is shown in Figure 3. C_{dS} is the basic discharge coefficient when P_{RS}* becomes infinity. P_{RS}* is the same as P_R* when C_d is equal to C_{dS}, and n is an empirically fitted parameter.

The LDSM model can select discharge coefficients for arbitrary wind directions and calculate ventilation flow rates using the formula (2) shown in Table 1. The inflow /outflow angles at the openings provide us with important information on the internal flow patterns.

2.2 COMIS-LDSM

The LDSM model was coupled with the COMIS code, as shown in Figure 4 (Ohba at al. 2008). 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. The calculation was performed by the Relaxation-Newton method with an under-relaxation factor of 0.5 and an absolute tolerance for ventilation flow rate of 8.3E-7. Ventilation flow rates, discharge coefficients and inflow/outflow angles at openings were obtained from the COMIS-LDSM model.

When TRNSYS calculates sensible loads, the ventilation flow rates obtained by the COMIS-LDSM model were used as input data for ventilation flow rates. The TRNSYS code provides us with room temperatures, sensible load and latent load et al.

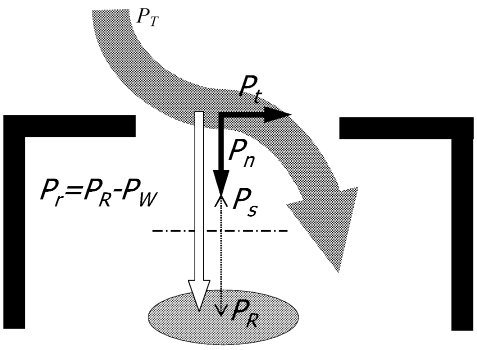


Figure 1. Dynamic similarity in vicinity of inflow opening

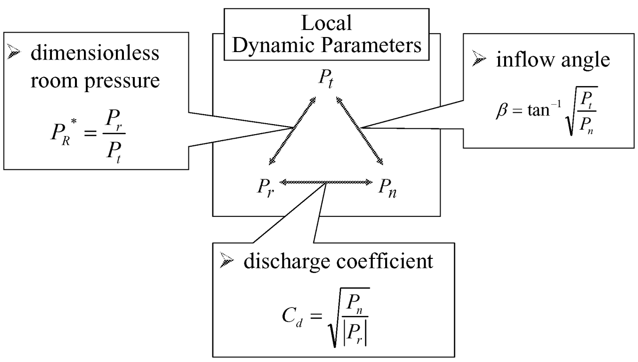


Figure 2. Local Dynamic Similarity

Table 1. Fundamental formulas of local dynamic similarity model

$$P_r = P_R - P_W \quad (1) \qquad Q = C_d A\sqrt{\frac{2}{\rho}|P_r|} \quad (2)$$

$$C_d = \sqrt{\frac{P_n}{|P_r|}} \quad (3) \qquad \beta = \tan^{-1}\sqrt{\frac{P_t}{P_n}} \quad (4)$$

$$P_R^* = \frac{P_r}{P_t} \quad (5)$$

$$C_d = C_{dS}\left(\frac{P_R^*}{P_{RS}^*}\right)^n \qquad (|P_R^*| \le |P_{RS}^*|) \quad (6)$$

$$C_d = C_{ds} \qquad (|P_R^*| \ge |P_{RS}^*|) \quad (7)$$

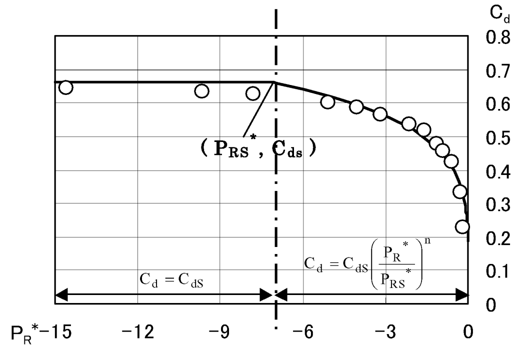


Figure 3. Ventilation performance expression for basic inflow opening

3. SIMULATION STUDY ON VENTILATION FLOW RATES AND SENSIBLE LOADS IN DETACHED HOUSE

This simulation study was performed for a typically shaped house defined by the Architectural Institute of Japan (AIJ). 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 stories and a total floor area of 120 m^2, comprising six rooms including a living room kitchen (LDK). The eave height was 5.4 m.

3.1 Input database of cross-ventilation for detached house model

Wind tunnel experiments were conducted using a house model with a scale of 1:40, as shown in Figure 5. The approach flow was a boundary layer flow with a power-law index of 0.25, and the reference velocity was kept at 7.0m/s at the eave height of the model.

The database of tangential dynamic pressure at openings was produced by Irwin's surface wind sensor (Irwin 1981), as shown in Figure 6. The details of this method were previously reported (Kurabuchi et al., 2005). The tangential wind velocities of U_t at 3.75mm from the wall and roof surfaces were measured by a split-film anemometer. The measuring height was equivalent to one eighth of the average opening height. The regression coefficient α and β in formula (8) were measured from several values of ΔP and U_t.

$$U_t = \alpha + \beta\sqrt{\Delta P} \tag{8}$$

With the calibration data, the P_t distribution on the wall and roof surface of the detached house model for an arbitrary wind angle was obtained with little time and effort.

The database of wind pressure on the model surface was collected by a multi-point manometer. Sampling frequency was 200 Hz, and averaging time was 60 seconds.

The ventilation performance of inflow /outflow openings was also provided from Figure 3 as input data. For inflow openings: C_{ds}= 0.67, P_{RS}*= -0.288, and n= 0.23. For outflow openings: C_{ds}= 0.67, P_{RS}*= 3.17, and n= 0.22. The C_d of the internal doors was set to a constant value of 0.63 for the present calculation.

3.2 Simulation study on ventilation flow rates in detached house

(1) Calculation methods

All windows and internal doors in rooms other than toilets and bathrooms were kept open. The inside and outside temperature was set to 20°C to maintain the conditions of wind-induced ventilation, because it was more

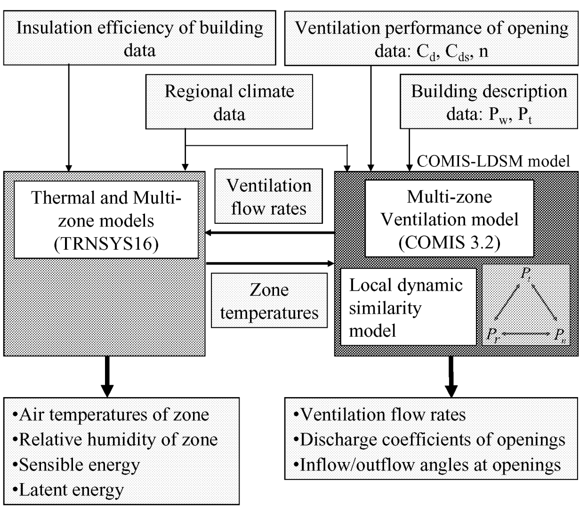
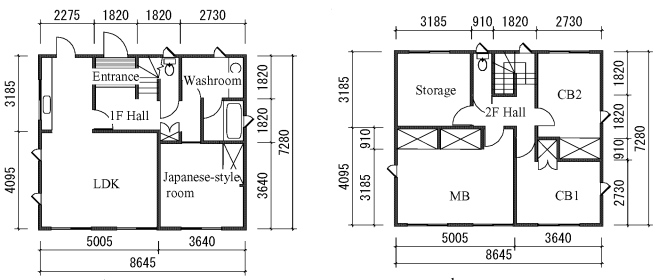


Figure 4. Block diagram of COMIS-LDSM model and TRNSYS model



1st floor plan 2nd floor plan

Figure 5. Floor plan of detached house model

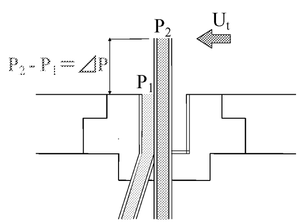


Figure 6. Surface wind sensor

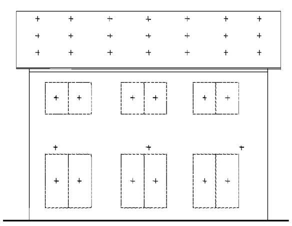


Figure 7. Measuring points of P_t in detached house model

reasonable to validate the COMIS-LDSM model than the conventional Orifice model. The reference velocity at the eave height was kept at 1.0 m/s.

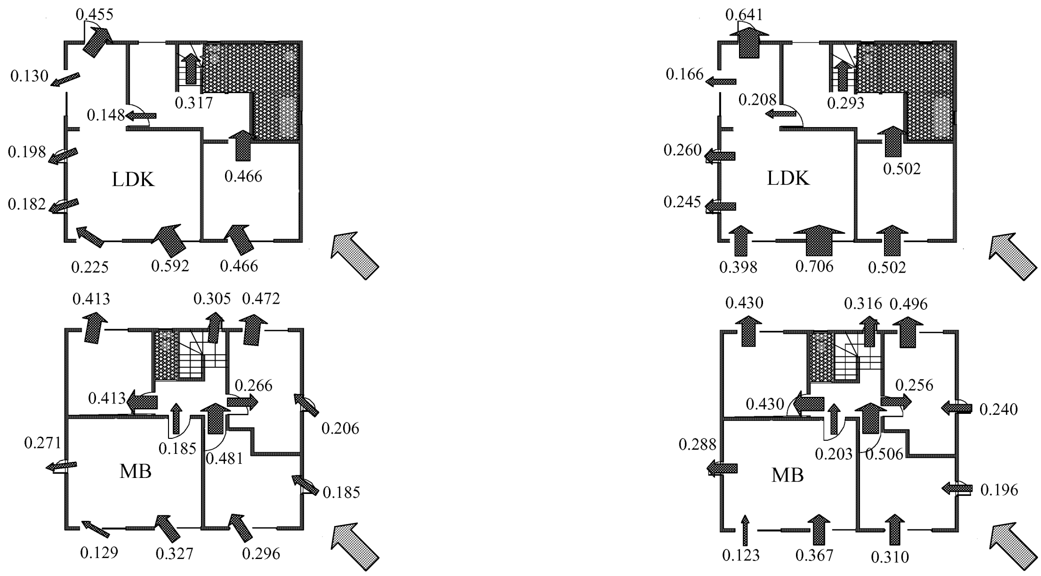
(2) Calculation results

Figure 8 indicates the inflow/outflow incident angles and ventilation flow rates in rooms for a wind angle of 135°. The Q value of 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 9 indicates the calculated ventilation flow rates in rooms for a wind angle of 135°. There was a large difference between the airflow rates of the conventional Orifice model and the COMIS-LDSM in the LDK, and the difference corresponds to 26 %. In the other rooms it was equivalent to 5-9 %.

Figure 10 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 by the COMIS-LDSM for wind angles of 45°, 135° and 315°, especially where the approaching flow was not normal to the upwind openings. This may have caused the poor prediction of cooling load reduction when utilizing cross-ventilation for saving energy consumption of the air-conditioning system.

3.3 Simulation study on sensible load in detached house



(1) COMIS-LSDM model (2) Orifice model [Dimensions in m³/s]

Figure 8. Calculated ventilation flow rates for wind angle of 135° when using COMIS-LDSM model and Orifice model

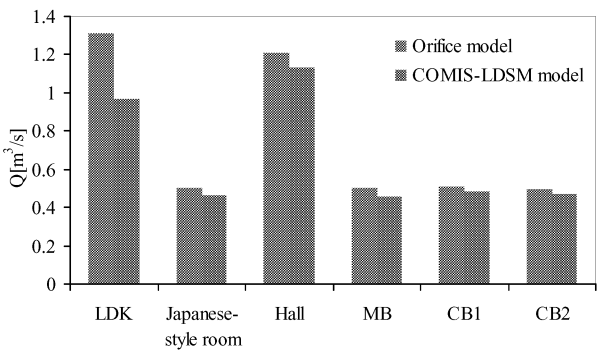


Figure 9. Calculated ventilation flow rates in rooms for wind angle of 135 °

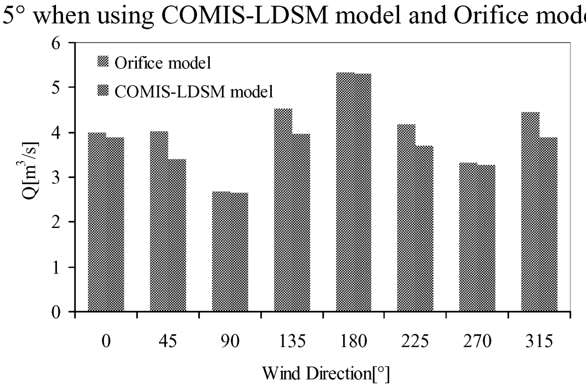


Figure 10. Calculated total ventilation flow rates in house for each wind angle

(1) Calculation methods

This simulation study was carried out to calculate the reduction effect of sensible cooling load when utilizing cross-ventilation.

The house surroundings were assumed to be vacant. The house's insulation efficiency was determined according to the energy-conversation standards following generation. Expanded AMeDAS weather data in Tokyo was used for metrological data. The analyzed date of 1st July was selected because cooling and normal window operations occurred during the day. The analyzed room was the LDK on the 1st floor. The schedule of persons at home was followed according to the schedule proposed by Udagawa (Udagawa, 1985, Nagai, 2006).

The decision tree of operation of cooling and windows is shown in Figure11. Simulation was carried out every 15 minutes to evaluate window status and air-conditioning operation in the LDK. If the room was not occupied or persons were sleeping in the room, all windows and internal doors were closed and the air-conditioner was turned off. All internal doors were opened if the windows were closed. If the room temperature in the LDK rose above 28 ^{o}C in an occupied room, then cooling was required and the room's air-conditioner was turned on. It was set to 28 ^{o}C and 60 %.

Three cases were tested in this simulation.

Case1: Only cooling operation. Windows were closed all day long.

Case2: Normal window operation. Ventilation flow rates calculated by Orifice model.

Case3: Normal window operation. Ventilation flow rates calculated by COMIS-LDSM model.

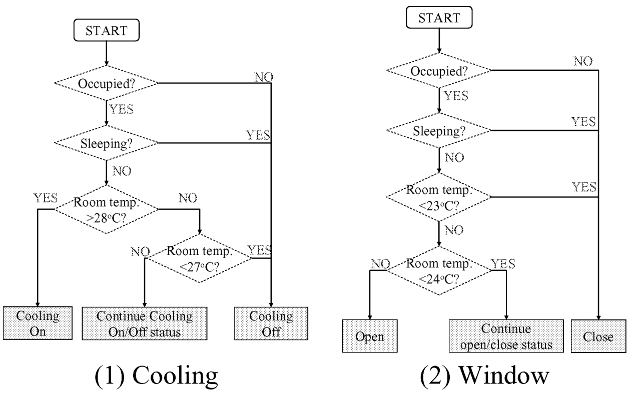
(2) Calculation results

Figure 12 shows window operation and room temperature in the LDK. In Case 1, the air-conditioner was operated when persons stayed in the room so that room temperature was kept constant at 28 ^{o}C. Room temperature in Case 3 was little bit higher than in Case 2 while windows were opened. The temperature difference between Case 2 and Case 3 in the period 0:00-6:00 was caused by the remaining effect of room temperatures occurred on previous date.

Figure 13 indicates sensible load in the LDK. In Case 1, the air-conditioner operated during the occupied time zone. The difference between the sensible heat loads of Case 2 and Case 3 occurred in the period 10:00 to 11:00 because in Case 2 windows were opened and cross-ventilation was working.

Figure 14 shows the air change rate in the LDK. The air change rate in Case 2 was two and 10 times larger than in Case 3 so that the duration of cross-ventilation in Case 2 was one hour longer than in Case 3.

Table 2 indicates the cumulative sensible load and reduction of cooling load achieved by utilizing cross-ventilation. Utilization of cross-ventilation succeeded in reducing the sensible load by 21~26 % compared to that when using the air-conditioner in Case 1. Cumulative sensible load in Case 2 using the conventional Orifice model for calculation of ventilation flow rates was estimated to be about 500 Watt smaller than that in Case 3 using the COMIS-



(1) Cooling (2) Window

Figure 11. Operation of cooling and window

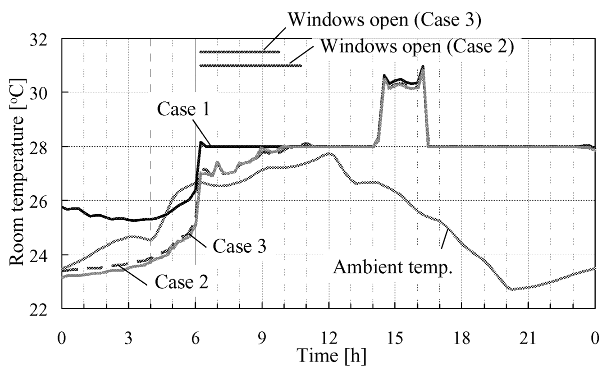


Figure 12. Room temperature in LDK

LDSM model.

4. CONCLUSIONS

A semi-empirical ventilation model based on the local dynamic similarity theory was coupled with COMIS and TRNSYS, which are widely used for energy conservation simulation. The COMIS-LDSM model provided us with valuable information on inflow/outflow angles at openings. It is very useful for predicting flow patterns in rooms.

A simulation study was performed on ventilation flow rates and heat loading in a detached house. The conventional Orifice model overestimated the ventilation flow rates compared to those by the COMIS-LDSM model, especially when the approaching flow was not normal to the upwind openings. Thus, the conventional Orifice model tended to overestimate energy reduction loads when utilizing cross-ventilation.

ACKNOWLEDGEMENT

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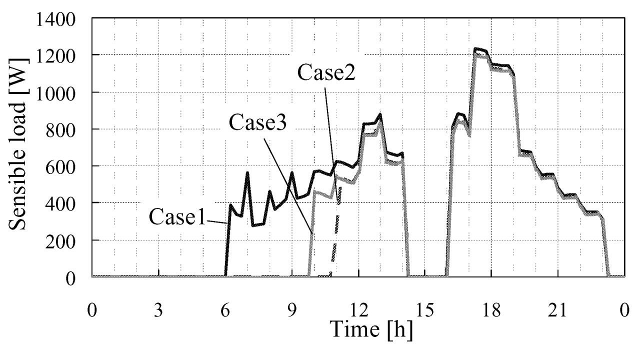

Figure 13. Sensible load in LDK

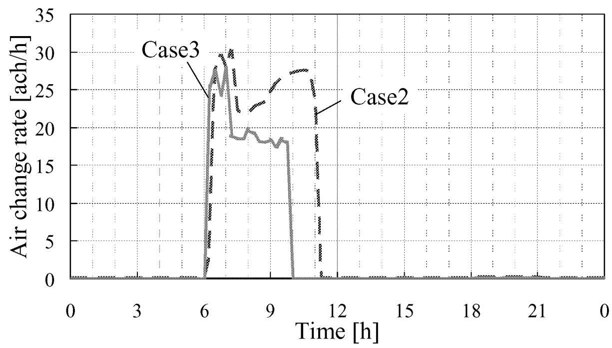

Figure 14. Comparison of air change rate estimated by Orifice model and COMIS-LDSM model

Table 2. Cumulative sensible load and reduction of cooling load by utilization of cross-ventilation

Case	Ventilation model	Window operation	Cumulative sensible load [W]	Reduction of cooling load [%]
1	Orifice	Closed	9480	—
2	Orifice	Opened/Closed	6986	26.3
3	COMIS-LDSM	Opened/Closed	7497	20.9