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PASSIVE VENTILATION BY THERMAL CONVECTION IN INSULATED HOUSES USING THE THERMAL CONCEPTS OF TRADITIONAL JAPANESE HOUSES IN SUMMER

M. Enai and N. Aratani
Department of Architecture, Hokkaido University
Sapporo, 060 Japan

k. Kubota and T. Ikenaga
Technical Department, Hokkaido Nikken Sekkei Ltd.
Sapporo, 060 Japan

The constructional concepts for comfortable living in the summer were confirmed in the traditional "Machiya" houses in the ancient city of Kyoto. One of the concepts is thermal convection ventilation by exhausting the warm air at the ceiling level. During the summer months in Hokkaido's capital city of Sapporo, the outdoor air temperature reaches 30 ℃ in the daytime, but becomes very cool at night.
In this paper, the convective airflow rates to obtain the cool outdoor air through upward openings were measured throughout the day by tracer gas techniques. The high ceiling space of the highly insulated test house was divided into five imaginary zones. The tracer gas (CO_2) was supplied in the bottom zone of the space. The gas concentrations in each zone were simultaneously measured and the airflow rates between one zone and the others were calculated from the measured concentrations. The results are discussed.

INTRODUCTION

As concern for indoor climate during the summer season in highly insulated houses increases, so has the need to measure the exhausted warm air and the inflow cool air in a living area. Though the traditional Japanese houses in the summer are relatively protected from outside heat by thick earthen outer walls covered by plaster, the inner spaces are open relatively to each other. Fundamental concepts for comfortable living in the sultry summer rely upon upward openings for the purpose of vertical ventilation by thermal convection. If the cool outdoor air flows adequately into dwellings through the upward openings, such as high side windows during the night, highly insulated and airtightened houses are able to maintain cool environments without the use of mechanical cooling equipment.
The convective airflow rates through such openings were measured in an actual highly insulated test house in Sapporo by utilizing tracer gas techniques. The high ceiling space of the test house was divided into five volumetrically equal zones. A tracer gas injection tube was installed in the bottom zone and the sampling tubes in each zone were connected to a manifold to produce an "average" sample. The tracer gas was

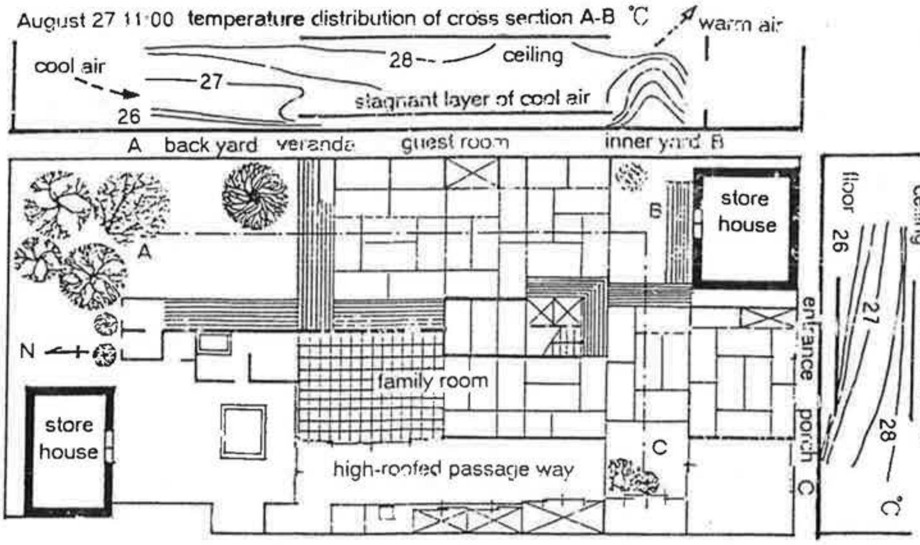


Fig.1 Temperature distribution of a Kyoto Machiya House in summer

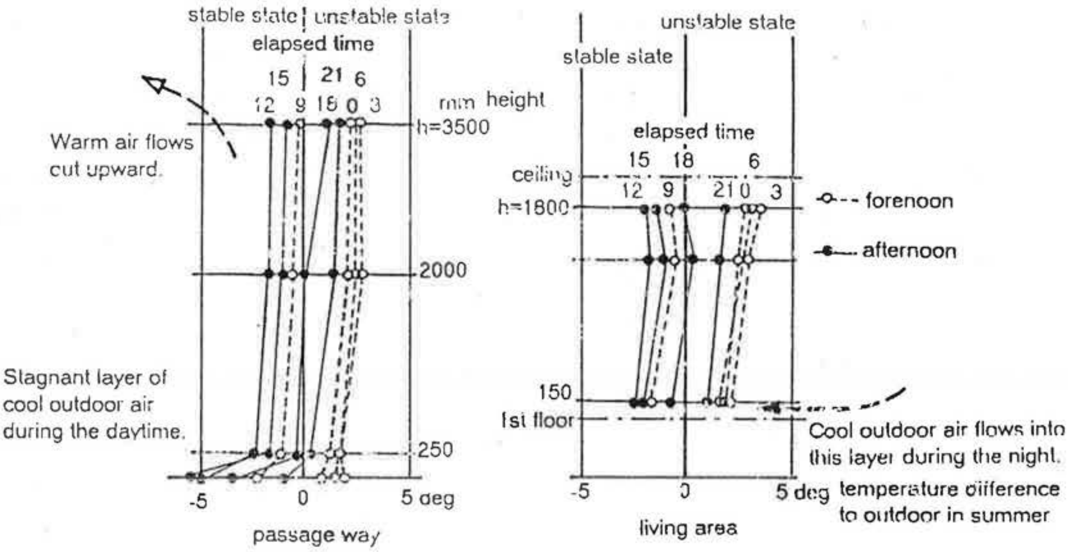


Fig.2 Vertical distribution of temperature from one elapsed time to the next

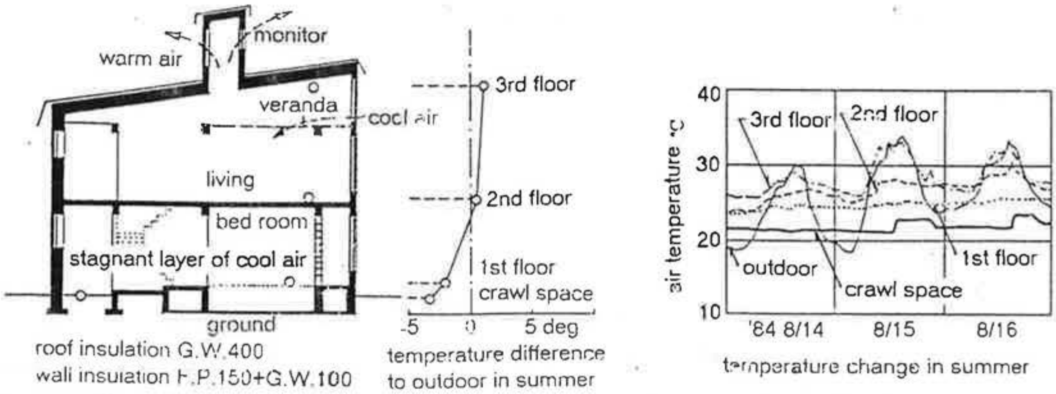


Fig.3 Thermal environment of highly insulated dwelling in Sapporo

supplied by both impulse injection method and constant injection method.
In this study, both methods were examined in the test house. The gas concentration fluctuations after impulse injection suggests general airflow processes between the five imaginary zones. The changes of gas concentrations during constant injection were used to calculate air change rates throughout the day. The main objective was to make clear the characteristics of the airflow systems through the upward openings in the living area by using the tracer gas techniques.

THERMAL CONCEPTS OF JAPANESE HOUSES

Traditional House Concepts:

We measured the thermal environment of several Machiya houses in Kyoto for six weeks during the hot summer. Fig.1 shows the temperature distribution in one of the houses. This type of house has several yards. The thick walls and the heavy plaster storehouses act as fire walls protecting the main occupant spaces. The walls and the storehouses also function as thermal insulation to keep the environment cool, and the deep thickets in the yards act as sunshades which cool the surrounding air. A layer of stagnant cool air at the first floor level is maintained in the daytime. Fig.2 shows the vertical distribution of temperature, based on the outdoor temperature from one elapsed time to the next.
At night, the cool outdoor air flows into the lower part of the occupant space and the warm air flows out from the higher part such as through the highroofed passage way. During the day, the cool air stagnates at the first floor level. This upward opening system for the ventilation by thermal convection and thermal storage of the crawl space is the wisdom of the traditional design which , to a marginal degree, maintains an environmental temperature equilibrium during the hot summer months.

Highly Insulated House Concepts:

We measured the thermal environment of a highly insulated house in Sapporo, Hokkaido. Fig.3 shows the sections of this house and the temperature distribution. The warm air is exhausted through the upper side openings and the ventilation is controlled by thermal convection. The room air temperature on the first floor is low and cool. In this case, the transition of room air temperature moves horizontally throughout the year, therefore, the indoor climate is not cold in winter and is never hot in summer. This is an important factor for energy conservation.

METHODS FOR MEASURING AIRFLOW RATES

Test House:

Fig.4 shows the main airflow processes as the vertical ventilation by thermal convection through upper openings in summer. To assess airflow rates and processes through the upper openings in summer, the high ceiling space of the Test House as shown in Fig.5 was divided into five imaginary zones. Fig.6 shows the floor plans of the Test House. The structure is of steel frame and the first floor is an earthen floor.

Systems for Measurement and Tracer Gas Injection:

Fig.7 shows the control and measurement system used to determine the airflow rates

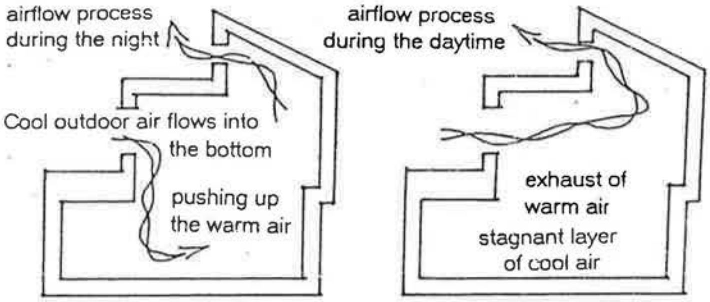


Fig.4 Airflow processes of upward openings in summer

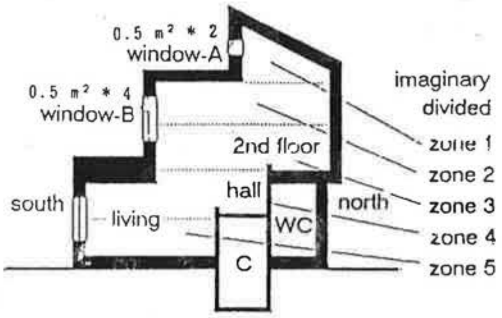


Fig.5 Cross section of Test House

Fig.6 Floor plan of Test House

Specifications of Test House

total floor area : 160 m^2, air volume of building : 390 m^3.

outside insulation : glass wool / 200 mm , efficiency of airtightness : 1.3cm^2/m^2.

air change rates when the windows were closed in summer : 0.15 ac/h.

covering ratio by window screens acting as sunshades : 50 %.

stored heat of electric equipment : 200w

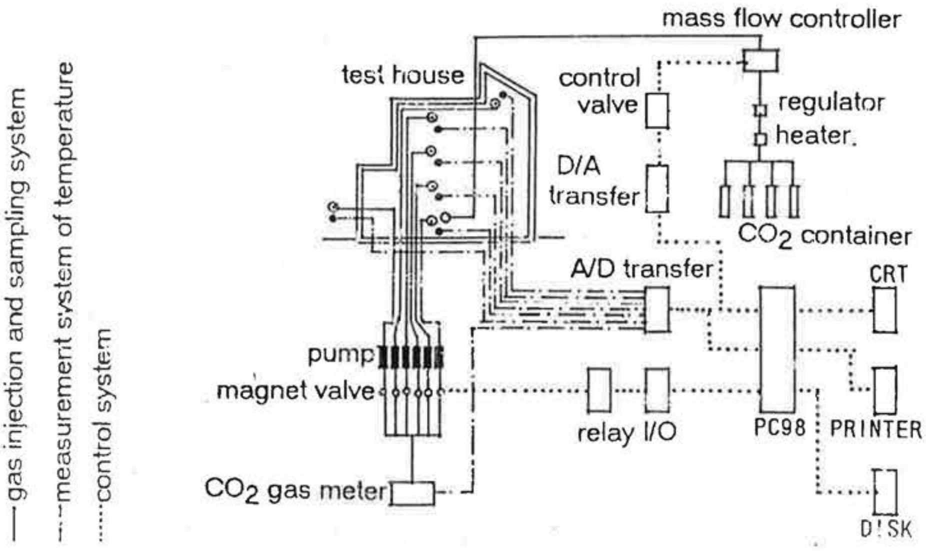
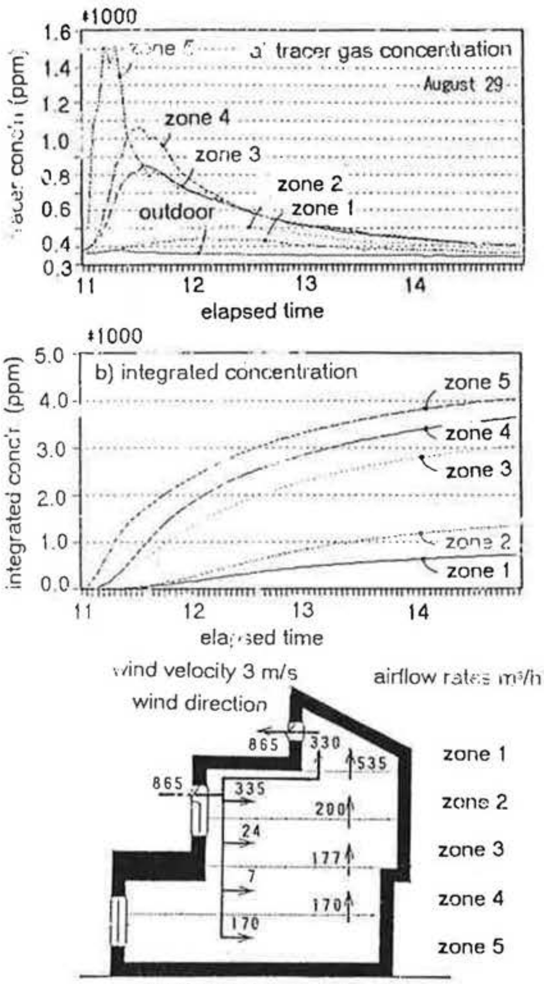
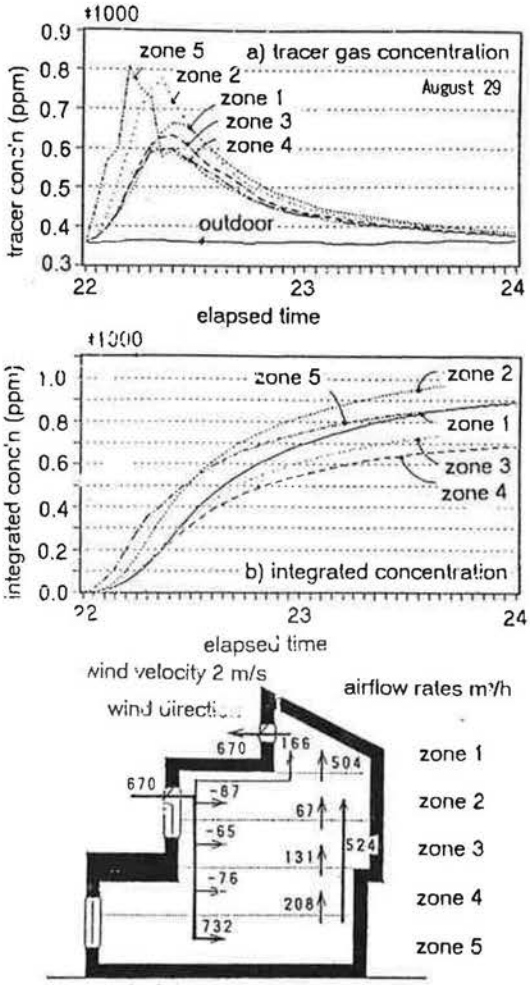


Fig.7 Control and measurement system



c) airflow rates and process

Fig.8 Airflow rates and processes during the daytime



c) airflow rates and process

Fig.9 Airflow rates and processes during the night

and their processes. A tracer gas injection tube was installed in the bottom zone and the sampling tubes in each zone were connected by manifold to obtain an "average" gas concentration in the central region.

The tracer gas (CO_2) was supplied by impulse injection (0.6 m^3/h * 0.25 h) method to determine the airflow processes and by the constant injection (0.2 m^3/h) method to assess the change of the airflow rates throughout the day. When the tracer gas is injected in the bottom zone, it is possible to decrease the influence of specific gravity of the tracer gas and not to disturb the air circulation in the space which has the temperature difference and the difference of the gas concentration.

TEST RESULTS

Infiltrated Outdoor Air Measured by Impulse Method:

Fig.8_a and Fig.9_a show the response of the gas concentration by impulse injection. During the daytime, the first peak of the response is in zone 5 and the second peak is

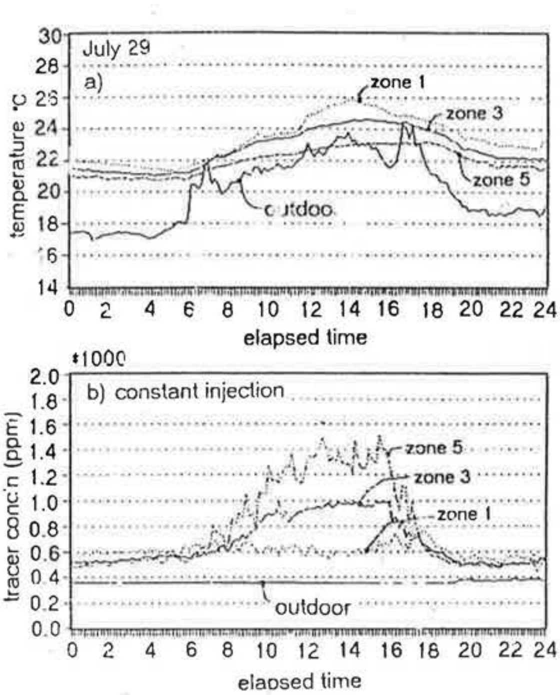


Fig.10 Change of temperature and tracer gas concentration

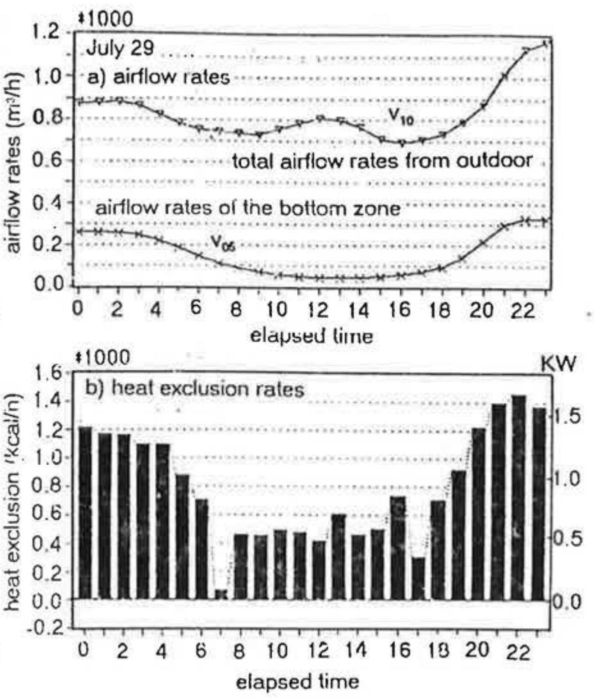


Fig.11 Change of airflow rates and heat exclusion rates to the outdoors

in zone 4. The peak appears in order from the bottom upwards. At night, the first peak of the response is in zone 5 and the second peak is in zone 2. The peak does not appear in order from the bottom to the next level. This would indicate that the airflow processes at night are not equal to those in the daytime.

We assumed that the airflows did not change during the interval of the measurement. The gas concentration integration was calculated for each zone during 2 and 4 hour intervals.

Each integrated value is equal to the destined gas concentration in the case of constant injection when the time interval for integration becomes infinite. Fig.8_b and Fig.9_b show the integrated concentration in each zone.

The simultaneous equations for calculating the airflow rates are as follows:

$$DC_i = \Sigma\ (C_{im}-C_{0m})*dt/T, \quad m = 0, 1, 2 \ldots, k, \quad dt*k = t \tag{1}$$

In the daytime:

$$DC_2*V_{21}-DC_1*V_{10} \quad -V_1*\{C_1(t)-C_1(0)\}/T = 0, \quad V_{01}+V_{21}-V_{10} = 0 \tag{2}$$

$$DC_3*V_{32}-DC_2*V_{21} \quad -V_2*\{C_2(t)-C_2(0)\}/T = 0, \quad V_{02}+V_{32}-V_{21} = 0 \tag{3}$$

$$DC_4*V_{43}-DC_3*V_{32} \quad -V_3*\{C_3(t)-C_3(0)\}/T = 0, \quad V_{03}+V_{43}-V_{32} = 0 \tag{4}$$

$$DC_5*V_{54}-DC_4*V_{43} \quad -V_4*\{C_4(t)-C_4(0)\}/T = 0, \quad V_{04}+V_{54}-V_{43} = 0 \tag{5}$$

$$-DC_5*V_{54} \quad +M_5-V_5*\{C_5(t)-C_5(0)\}/T = 0, \quad V_{05} \quad -V_{54} = 0 \tag{6}$$

At night, Equations (3) and (6) become as follows:

$$DC_3*V_{32}-DC_2*V_{21}+DC_5*V_{52}-V_2*\{C_2(t)-C_2(0)\}/T = 0, \quad V_{02}+V_{32}-V_{21}+V_{52} = 0 \quad (3)'$$

$$-DC_5*V_{54}-DC_5*V_{52}+M_5-V_5*\{C_5(t)-C_5(0)\}/T = 0, \quad V_{05} \quad -V_{54}-V_{52} = 0 \quad (6)'$$

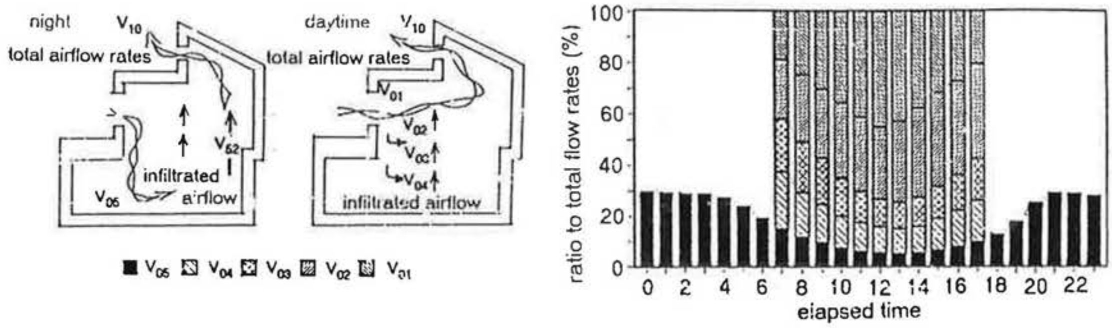


Fig.12 Change of ratio of infiltrated airflow rates throughout the day

In this case, the gas balance equation in zone 2 has to be added into the above ten simultaneous equations (2) to (6) at the appropriate time t_a.

$$V_2*\{dC_2(t_a)/dt\} = C_0(t_a)*V_{02}+C_3(t_a)*V_{32}-C_5(t_a)*V_{52}-C_2(t_a)*V_{21} \quad (7)$$

where

DC_i : destined gas conc'n in zone i m^3/m^3 , C_0 : gas conc'n of outdoor m^3/m^3

$C_i(t)$: gas conc'n in zone i at the time t m^3/m^3 , dt : time interval for measurement h

T : time interval of injection h , M_i : injection rates in zone i m^3/h

V_{ij} : airflow rates from zone i to zone j m^3/h , t : time interval for integration h

Fig.8_c and Fig.9_c show one of the calculated results as airflow rates and processes. In the daytime, most of the airflow from the outdoor is exhausted directly through the upper openings as shown in Fig.8_c.

At night, most of the airflow through the lower openings flows into the bottom zone. Following which, there is a strong airflow from the bottom zone to zone 2. The small arrows indicate the airflow in order from one zone to the next. Thus, the airflow processes in the daytime are different from those at night.

Air Change Rates Measured by Constant Injection:

Fig.10_a shows the change of air temperature and Fig.10_b shows the change of the gas concentration in the case of constant injection throughout the day, respectively.

The simultaneous equations for calculating the airflow rates are as follows.

In the daytime,

$$V_1*\{dC_1(t)/dt\} = C_0(t)*V_{01}+C_2(t)*V_{21}-C_1(t)*V_{10} \quad ,V_{01}+V_{21}-V_{10}=0 \quad (8)$$

$$V_2*\{dC_2(t)/dt\} = C_0(t)*V_{02}+C_3(t)*V_{32}-C_2(t)*V_{21} \quad ,V_{02}+V_{32}-V_{21}=0 \quad (9)$$

$$V_3*\{dC_3(t)/dt\} = C_0(t)*V_{03}+C_4(t)*V_{43}-C_3(t)*V_{32} \quad ,V_{03}+V_{43}-V_{32}=0 \quad (10)$$

$$V_4*\{dC_4(t)/dt\} = C_0(t)*V_{04}+C_5(t)*V_{54}-C_4(t)*V_{43} \quad ,V_{04}+V_{54}-V_{43}=0 \quad (11)$$

$$V_5*\{dC_4(t)/dt\} = C_0(t)*V_{05}-C_5(t)*V_{54}+M_5 \quad ,V_{05} \quad -V54=0 \quad (12)$$

At night, Equations (8) to (12) have to become as follows because of the bypass flow.

$$\Sigma\ V_i*\{dC_i(t)/dt\} = C_0(t)*\Sigma\ V_{0i}(t) \quad +M_5\ ,\ \Sigma\ V_{0i} \quad -V_{10}=0 \quad (13)$$

$$V_5*\{dC_5(t)/dt\} = C_0(t)*V_{05}(t) \quad -C_5(t)*V_{54}+M_5\ ,\quad V_{05} \quad -V_{54}=0 \quad (14)$$

Fig.11_a shows the change of the airflow rates. The airflow rates into the bottom zone increase when the outdoor temperature falls at night. The airflow rates into the bottom zone decrease when the outdoor temperature rises during the daytime. The total airflow rates exhausted through the upper openings bring out the stored heat in the high ceiling space. Fig.11_b shows the heat exclusion rates from the main occupant space. Generally, the stored heat per total floor area is 10 w/m^2 in Hokkaido. The results of Fig.11_b mean that these highly insulated houses are able to maintain cool environments without mechanical cooling equipment.

Fig.12 shows the ratio of the infiltrated airflow rates. In the case of constant injection, we can not calculate the infiltrated airflow rates into each zone at night because of the strong bypass flow from the bottom zone to the upper zones. However, we are able to obtain the airflow rates such as the results of Fig.12 from the outdoor to each zone in the daytime by utilizing the constant injection method.

CONCLUSION

(1)Adequately insulated houses have a closed style against the heat from the outside in the summer. In such a case, the fundamental concepts to live comfortably in the hot summer require the upward openings for the vertical ventilation by thermal convection to exhaust the stored heat.

(2)The convective airflow rates were measured in an actual highly insulated test house in Sapporo by using tracer gas techniques. As the impulse of tracer gas was injected, the general airflow processes at night and in the daytime were made clear by using integrated gas concentration. At night, most of the cool outdoor air introduced through the lower openings flows into the bottom zone. In the daytime, most of the outdoor air flows directly out through the upper openings. The airflow processes at night are not equal to those in the daytime. Impulse injection is therefore a useful method to predict the airflow processes.

(3)The gas concentrations in each zone, when using constant injection, fluctuated throughout the day. The total airflow rates can be calculated according to the change of the gas concentration in zone 1. The ratio of the infiltrated airflow rates were made clear from measuring the gas distribution, especially those in the daytime. Constant injection is therefore a useful method to measure the change of the airflow rates throughout the day.

ACKNOWLEDGMENT

The authors are very grateful to Mr. Kurata, Dr. Hirokawa (University of Kyoto), Mr. Yamamtoto and Mr. Imanishi. They helped us study the thermal environment of the traditional houses and to apply the tracer gas techniques to the upward openings space of the highly insulated house.

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