PREDICTION OF INDOOR AIR QUALITY IN HOUSES WITH CONCENTRATION-CONTROL-VENTILATION SYSTEMS CONSIDERING THE CONCEALED AIR LEAKS AND DWELLERS OPENING BEHAVIOUR

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ABSTRACT

In order to find an effective method to keep indoor air quality good through the year in real houses, a simulation program: Fresh was reformed to integrate several important factors in Japanese detached houses and named "Fresh2010". The factors are infiltration from the concealed spaces, behaviour of window openings, the kind of ventilation systems and a concentration control systems. The present dwellers' habits of opening windows may be one of the factors in causing indoor air pollution. The concentration control ventilation with proper design may keep indoor air quality good through a year.

INTRODUCTION

There are many infiltration routes in Japanese traditional wooden houses. The equivalent leakage areas of recent houses have become smaller but three remain infiltration routes in the concealed spaces: beam spaces, crawl spaces and inside wall spaces. The authors made it clear that these routes lead chemical compounds into the indoor spaces from the concealed spaces in test houses as shown in Figure 1. Therefore, careful consideration of the infiltration from concealed spaces was given to the new building code in 2003. This building code required the regulation of the emission rate of formaldehyde from materials and the continuous ventilation systems in all rooms. However, the latest studies showed that most dwellers switch off the ventilation systems in mild seasons. Dwellers open windows in mild days and they will think that mechanical ventilation is needless. In some cases, dwellers do not use ventilation systems even in winter. These present conditions should not be ignored and it is necessary to investigate the indoor air quality and the method to prevent indoor air pollution in these houses built according to the building code in 2003.

In this study, in order to find an effective method to keep indoor air quality good through the year in real houses, simulation using "Fresh" was improved. This program was reformed to integrate several important factors in Japanese detached houses and named "Fresh2010". The factors are, infiltration from the concealed space, dwellers' behaviours of opening windows and the kind of the ventilation systems: an exhaust ventilation system, an exhaust and supply ventilation system and a concentration control system. The concentration control ventilation is one of the effective methods for continuous ventilation through a year.

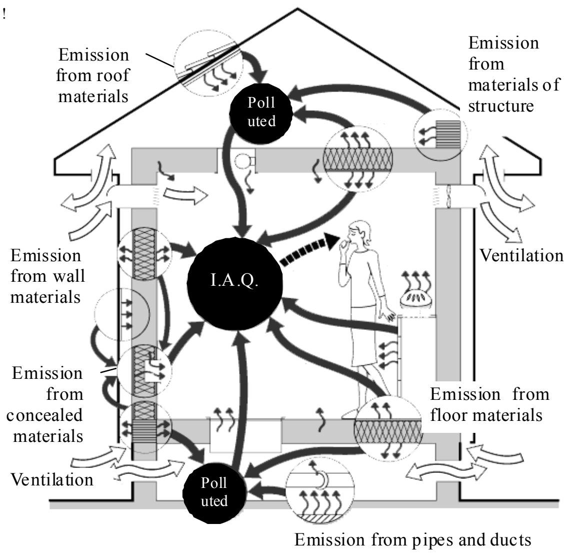

Figure 1 Influence of concealed pollution sources

SIMULATION METHODS

In former studies, the equivalent leakage areas in the concealed spaces were measured using cut models of wooden structures. The structures are a common post-and-beam wooden structure, an improved post-and-beam wooden structure and a wooden (2 inch x 4 inch) stud structure. The second and last structures are built according to the latest building insulation code established in 1999.

It was difficult to measure the equivalent leakage areas of the concealed spaces. Therefore, the cut models of these structures were set in a laboratory. Figure 2 shows a cut model of improved post-and-beam wooden structure. The sizes of the elements of the cut model are the same as those of elements of real houses but the cut model was lower than the real houses. Carpenters made these cut models in the laboratory.

Leakage areas in the concealed spaces were measured using mass-flow controllers and pressure analysers. Figure 3 shows the measurement system. When the leakage areas between cell1 and cell2 are measured, cell1 opened to the outside. The air pressures of cell3 and cell4 are adjusted to meet the pressure of cell2. On this condition, the air of cell2 goes only to cell1. The airflow rate from cell2 to cell1 accords with that through the mass-flow controller between the air tank and cell2. Therefore, the airflow rate is calculated.

Figure 2 Cut model of post-and-beam wooden structure

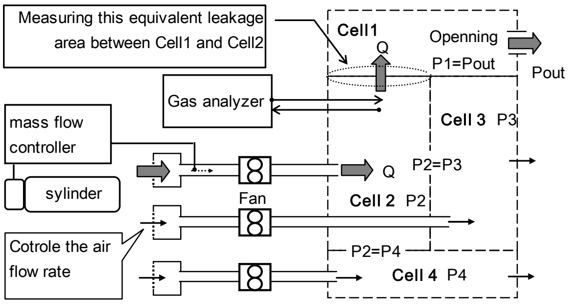

Figure 3 Measurement system of leakage areas between cells

The movements of chemical compounds were calculated using a simulation program. The program simulates the temperatures, the airflow rates, the concentrations and the generation rates of pollutants like formaldehyde: HCHO, carbon dioxide: CO_2 using the NHK standard living schedule model and the HASP weather data on Tokyo.

The simulation program was written in 1996, and was named 'Fresh96'. It was composed of the following three calculation methods.

(1) Dynamic thermal calculation of the temperature, heating and cooling loads.

Dr.Aratani devised the calculation method in 1974. The initial responses of the thermal-flow rates are calculated. The following equation was proposed in order to increase the speed of the calculation.

$$h(t) = B_0+\Sigma B_m e^{-\beta m \cdot t} + q \cdot \delta(t) \quad (1)$$

Where, $h(t)$ the initial response of thermal-flow rate, B_0 the steady value of thermal flow rate, $q=\Sigma B_m/\beta_m$ and $\delta(t)$ Delta function.

The temperatures and the heating and cooling loads are calculated with the above equation using Duhamel's integration method. The temperature and the heat loads are calculated using the temperatures in the other rooms and the ventilation rates Δt before. In the following case studies, the interval time Δt is set to be 5 minutes. The values are calculated using the standard weather data from Society of Heating, Air-conditioning and Sanitary Engineers of Japan and the rates of solar radiation through the windows are calculated considering the effect of shades. The thermal loads by human behaviors such as cooking, watching television and cleaning rooms, are calculated from the daily schedule model of a family. The air-conditioner and the windows are operated to make the indoor climate comfortable considering the daily schedule of a family. The air-conditioning systems and the windows are controlled as follows: The room temperatures are controlled to be above 22deg.C with a central heating system. The room temperatures are controlled to be above 22deg.C and below 28deg.C by opening windows in houses with a central heating system. The room temperatures are controlled to be below 28deg.C by cooling the rooms.

(2) Calculation of air flow rates in the multi-cell system

An equation of the power at the openings: the airflow rates are calculated using the following equations which are led by the balances of power at openings is used.

$$[D] \cdot \{q^n\}+[K]\{\int qdt\} = \{F_{wind}\}+\{F_{temp}\}+\{F_{fan}\} \quad (2)$$

where q *the* airflow rate, n the exponent of airflow friction, $[D]$ the matrix of airflow friction, $[K]$ the matrix of room air elasticity, $\{F_{wind}\}$ the power of wind, $\{F_{temp}\}$ the power by the room air density $\{F_{fan}\}$ the power of fan.

The equations can be solved using Newmark's numerical integration method. The ventilation rates are calculated considering the stack effect, the wind pressure and the mechanical power using the standard weather data, the ratios of wind pressure, the ratio of wind speed considering the circumstances and the performance of the fans. In the case of the following studies, the ratio of wind speed at the town to the speed at the plain flat ground was 0.4.

(3) Dynamic calculation of concentrations of pollutants

An equation of the amount of pollutants: the concentrations of pollutants in each room are calculated using the following equations which are led by the balance of the volume of the pollutants is used.

$$[Q] \cdot \{C(t)\}+[V] \cdot \{C'(t)\}=\{M(t)\} \quad (3)$$

where *[Q]* the matrix of airflow rate *Q(i,j)*: the airflow rate from room-i to room-j, $Q(k,k)= -\Sigma_{k<>i}Q(k,i)$, *C(t)* the concentration of a pollutant, *[V]* the volume of rooms, *{M}* the emission rates of a pollutant in each room.

The equation can be solved using Newmark β numerical integration method. The emission rates of CO_2 are set using the average Japanese daily schedule and the data on the emission rates caused by the dwellers' behaviours in houses. The daily schedule of each family is set considering the plan of the house. Figure 4 shows the calculated emission rates of CO_2. The emission rates of CO_2 are influenced by the behaviour of the family. The emission rates are high in the bedrooms on the second floor at night and the emission rates are high in the living room on the first floor at daytime. This is the pattern of emission rate of CO_2 in a general Japanese detached house.
The emission rate of formaldehyde was calculated using an equation with the consideration of the influences of temperature and sink.

$$E = E_{25}(t) \cdot a^{(T-25)} - \beta \cdot C(t) \qquad (4)$$

Where E: emission rate (μg/(h · m^2)), E_{25} (=100 μg/(h·m^2)): emission rate measured in small chamber when temperature is 25deg.C, T: temperature, a=1.11: measured in small chamber, β (= 0.06): ratio of sink measured in small chamber, C(t): concentration (μg/m^3)
E_{25} is influenced by the emission ability of materials. The ability was supposed to be in proportion to the quantity of pollutant in material. Therefore, E_{25} is shown as the following equation.

$$E_{25}(t) = E_{25}(0) \cdot M(t)/M(0) \qquad (5)$$

Where M(t): the quantity of pollutant in material.

Initial formaldehyde emission rates in the concealed spaces are set to be 100 μg/(h·m^2) considering the surface area of emission sources like plywood. The concentration of carbon dioxide: CO_2 is 400ppm.

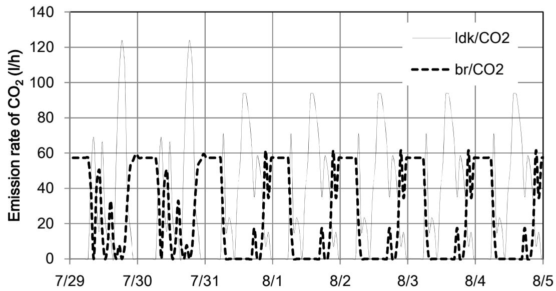

Figure 4 Emission rates of CO_2 in a week

Figure 5 shows a network of a simulation model with an exhaust ventilation system without a concentration sensor. The equivalent leakages in the model were set using the measurement results of the cut model. The simulation of an airtight test using a fan shows that the equivalent leakage area per its floor area is 2.8 cm^2/m^2. The ventilation system is a hybrid ventilation system. The air of utility is exhausted through a stack and the outside air is supplied to L.D.K and bedrooms through ventilators. The airflow rate is controlled using a fan, a damper and a sensor. The fan and the damper are operated every 5 minutes using an airflow sensor.

Table 1 shows simulation models with several ventilation systems. In the case of a supply and exhaust ventilation system, the outside air is supplied

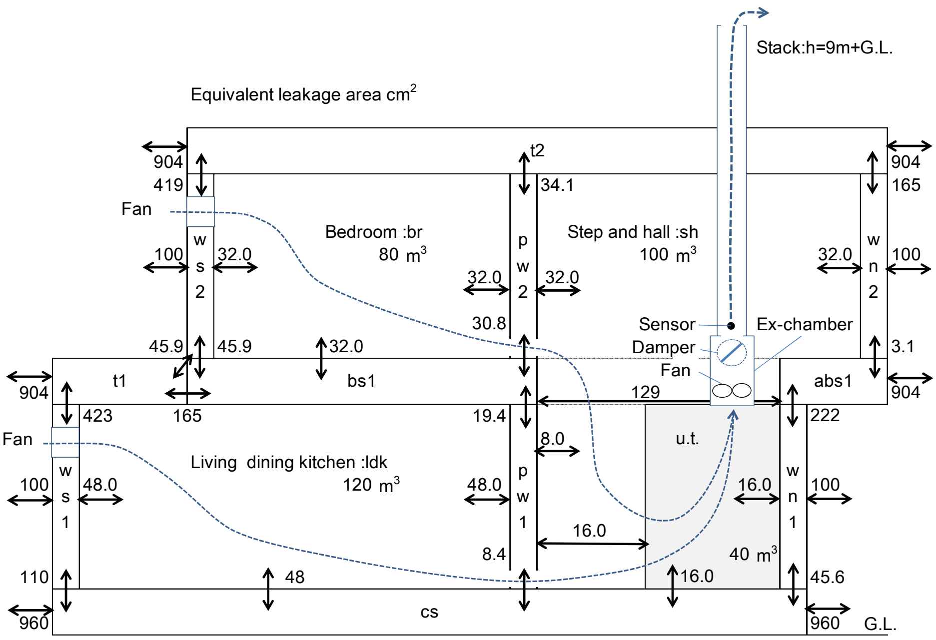

Figure 5 Leakage network of simulation model with exhaust system

to L.D.K and bedrooms through a supply-chamber and ducts. The airflow is controlled with the same method for exhausting. The airflow is controlled between 128 m^3/h and 150 m^3/h.

In this study, the ventilation systems with the concentration sensor of carbon dioxide or formaldehyde are investigated as shown in Table 2. In these cases with a concentration sensor, the airflow rate is controlled so that the concentration of exhaust air may meet the target concentration. The airflow rate is controlled at the interval of 50 m^3/h every 5 minutes. In order to keep the indoor concentrations steady, the concentration sensor and fan are required in every room. The method is simple but expensive. In this study, systems with a single concentration sensor are investigated.

Table 1 Vantilation system of simulation models without concentration censor

	Exhaust fan(m^3/h)		Supply fan(m^3/h)				Ventilator(cm^2)	
	ut	Dumer	ldk	br	Total	Dumer	ldk	br
S&E:Supply and Exhaust	128	<150	64	64	128	<150	-	-
E: Exhaust	128	<150	-	-	-	-	64	64

Table 2 Models for simulations

Sensor	Target concentration	Name of model	
-	-	S&E:Supply and Exhaust	E: Exhaust
Carbon dyoxide	1000 ppm	S&E +CO2_1000ppm	E +CO2_1000ppm
Carbon dyoxide	800 ppm	S&E +CO2_800ppm	E +CO2_800ppm
Carbon dyoxide	600 ppm	S&E +CO2_600ppm	E +CO2_600ppm
Formaldehyde	100μg/m^3	S&E +HCHO_100μg/m^3	E +HCHO_100μg/m^3
Formaldehyde	60μg/m^3	S&E +HCHO_60μg/m^3	E +HCHO_60μg/m^3
Formaldehyde	40μg/m^3	S&E +HCHO_40μg/m^3	E +HCHO_40μg/m^3

RESULTS

Figure 6 shows the temperatures. The temperatures in all the models are almost the same. Figure 7 to 21 show the results of an exhaust system without a concentration censor.

Airflow rate in an exhaust-stack is almost steady by the effect of control using a fan and damper with the exception of the rate on the windy day as shown in Figure 7. The ventilation rate of L.D.K.: VR of LDK is steady in winter and mild seasons as shown in Figure 8. The ventilation rate is higher than the rate of outside air supply to the space: OA to LDK for these seasons. The difference is caused by the infiltration through the concealed spaces. In summer, these rates fluctuate because of window opening in the bedroom.

Figure 9 shows the result of the bedroom. The outside air supply rate is low in winter. The outside air is not led through the ventilators because of the temperature difference. The rate is high in summer because of window opening. In most days in summer, L.D.K. is cooled in the daytime. At night, the bedroom is not cooled and windows are opened. Therefore, the ventilation rate of the bedroom increases and the rate of L.D.K. decreases.

Figure 10 to 12 show the CO_2 concentrations. The concentration of exhaust air is steady and almost lower than 1000 ppm. However, the concentration in L.D.K is higher than 1000 ppm in summer. The concentration of the bedroom is high in winter and mild seasons. These results can be explained by the characteristics of ventilation.

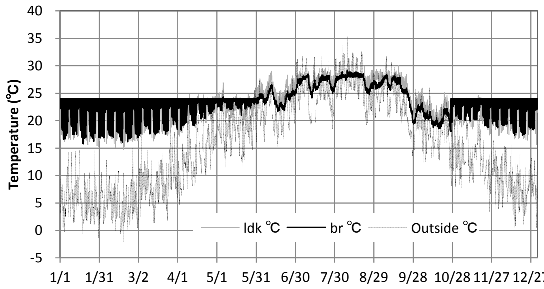

Figure 6 Ambient temperature of weather data and indoor temperatures

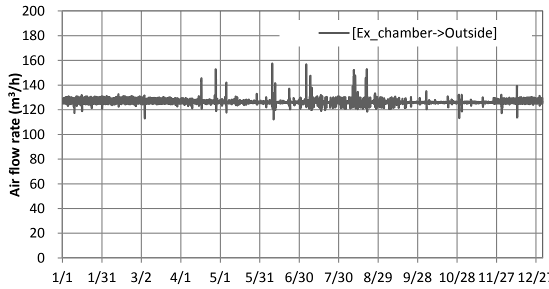

Figure 7 Air flow rate of exhaust-stack in a house with an exhaust system

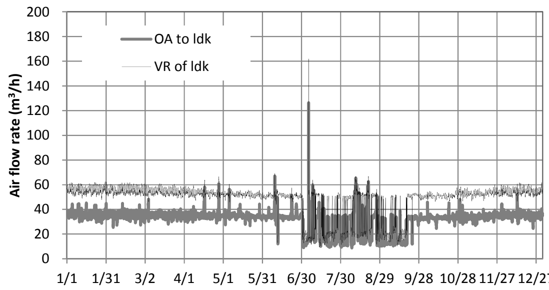

Figure 8 Outside air supply rate and ventilation rate of L.D.K. in a house with an exhaust system

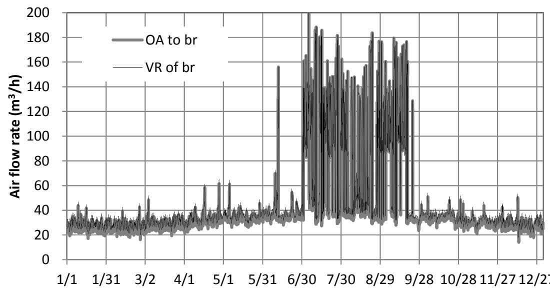

Figure 9 Outside air supply rate and ventilation rate in bedroom in a house with an exhaust system

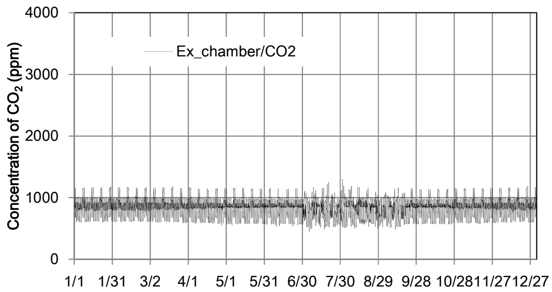

Figure 10 CO_2 concentration of exhaust air in a house with an exhaust system

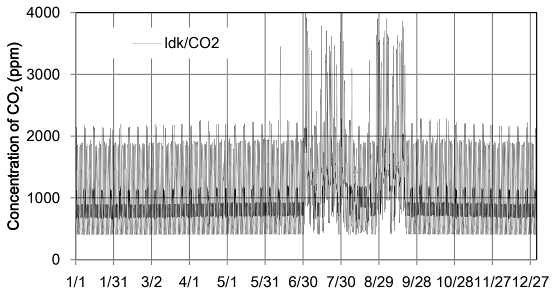

Figure 11 CO_2 concentration of LDK in a house with an exhaust system

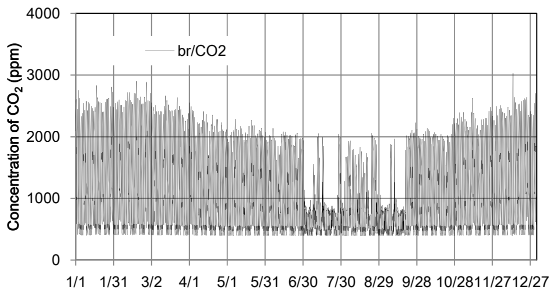

Figure 12 CO_2 concentration of bedroom in a house with an exhaust system

Figure 13 to 15 show the emission rates and the concentrations of formaldehyde. The emission rate changes with the temperature and the decrease of emission ability. The emission rate in concealed space: truss space, wall cavity, ceiling space and crawl space is higher than that of indoor space. The concentration on the exhaust air is high before summer and after that decreases. The concentration in L.D.K is high in summer and that in the bedroom is high in winter as shown in Figure 15.

Figure 16 and 17 show the daily changes of concentration of carbon dioxide in winter. The concentration changes with the dwellers' daily schedules. The concentration in L.D.K is very high in summer. When the dwellers open windows in bedrooms, the rate of outside air supply decreases with the pressure difference in L.D.K.

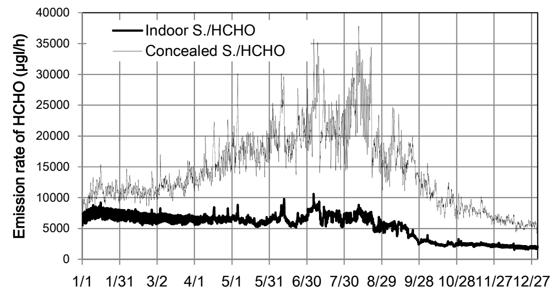

Figure 13 HCHO concentrations of indoor space and concealed space in a house with an exhaust system

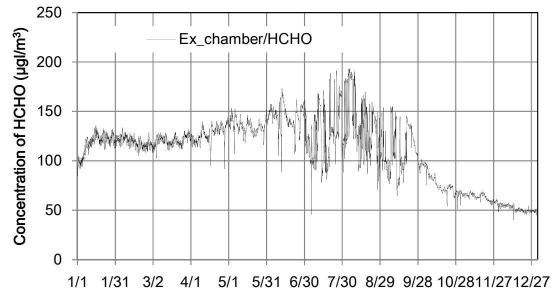

Figure 14 HCHO concentrations of exhaust air in a house with an exhaust system

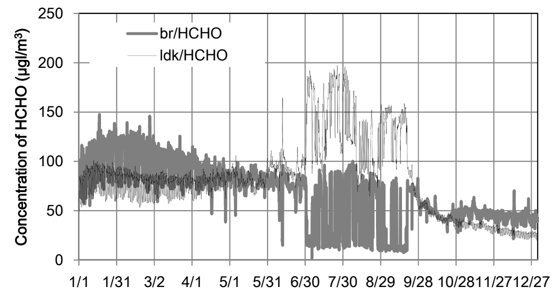

Figure 15 HCHO concentrations of LDK and bedroom in a house with an exhaust system

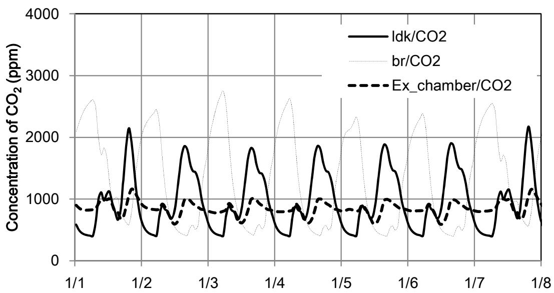

Figure 16 CO_2 concentrations in a house with an exhaust system in winter

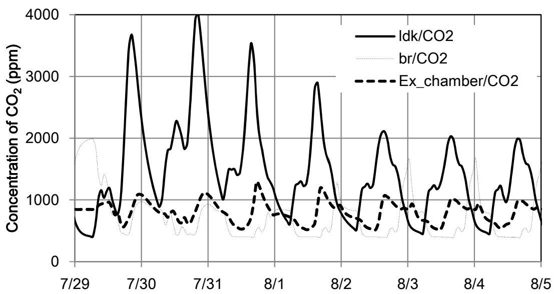

Figure 17 CO_2 concentrations in a house with an exhaust system in summer

Figure 18 to 21 show the emission rates and concentrations of formaldehyde. The emission rate changes with temperature. The rates in concealed spaces are very high in summer because of the influence of ambient high temperature. The concentration is high in L.D.K at daily time.

Figure 22 and 23 show the results of the supply and exhaust system. The concentration is not high in L.D.K., because a fan supplies the outside air continuously.

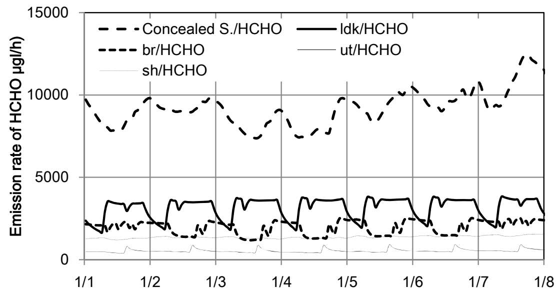

Figure 18 HCHO emission rates in a house with an exhaust system in winter

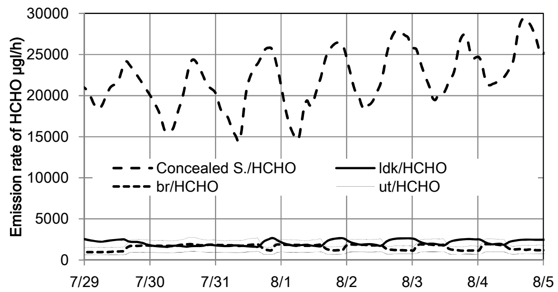

Figure 19 HCHO emission rates in a house with an exhaust system in summer

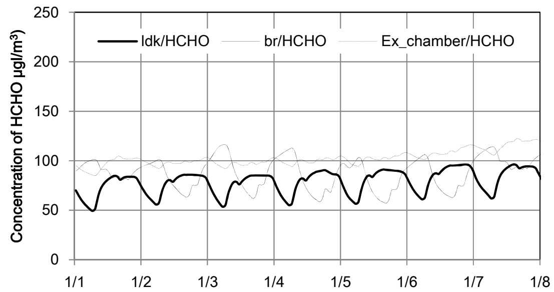

Figure 20 HCHO concentrations in a house with an exhaust system in winter

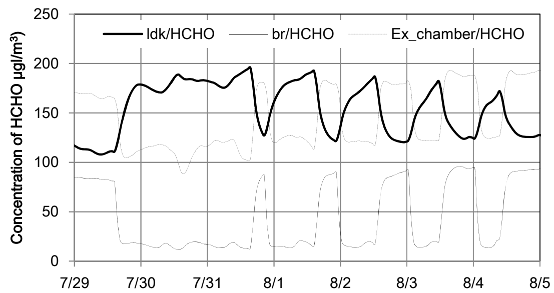

Figure 21 HCHO concentrations in a house with an exhaust system in summer

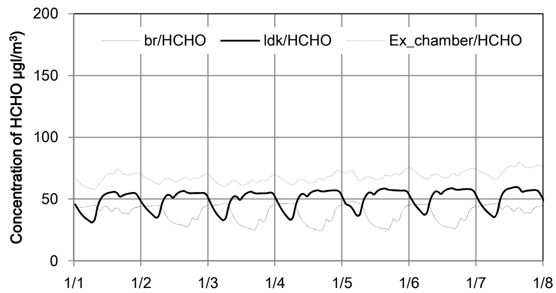

Figure 22 HCHO concentrations in a house with a supply and exhaust system in winter

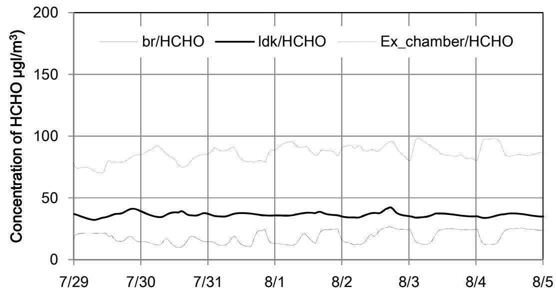

Figure 23 HCHO concentrations in a house with a supply and exhaust in summer

Figure 24 to 27 show the results of an exhaust system with a formaldehyde concentration sensor. The target concentration is 100 µg/m^3. The airflow rate in an exhaust stack is almost steady and the formaldehyde concentration is not high in winter. However, the airflow rate and the concentration in the exhaust stack fluctuate in summer. The emission rate changes rapidly with the temperature, so the system cannot control the concentration enough and the concentration of L.D.K. is higher than the target concentration.

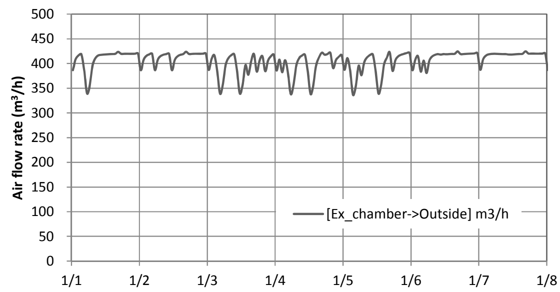

Figure 24 Airflow rate of stack in a house with an exhaust system with HCHO sensor in winter

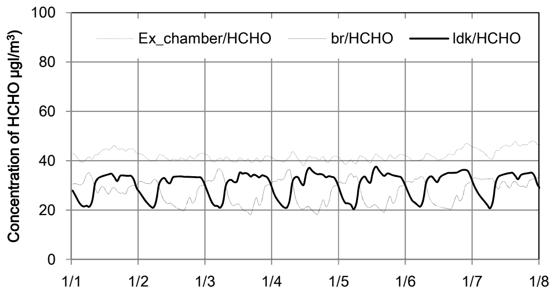

Figure 25 HCHO concentrations in a house with an exhaust system with HCHO sensor in winter

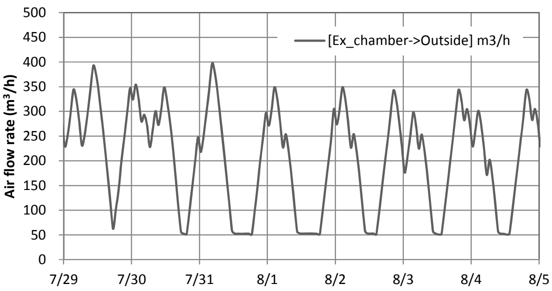

Figure 26 Airflow rate of stack in a house with an exhaust system with HCHO sensor in summer

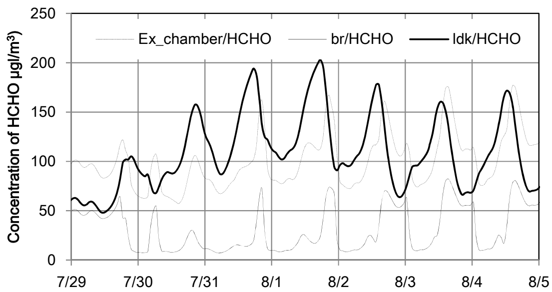

Figure 27 HCHO concentrations in a house with an exhaust system with HCHO sensor in summer

Figure 28 and 29 show the averages of air supply rates in a week: 1/1-1/7 of winter. 'OA to ldk' shows the outside air supply rate to L.D.K. through ventilators or a supply-chamber. 'OA to br' is that to bedrooms. 'Other OA' is an infiltration rate including the rate through the concealed spaces. The air supply rate in the case that the target concentration of carbon dioxide is 100 ppm, is lower than that without a concentration sensor. The relationship is also found in the case of formaldehyde. If the target concentration is lower, the total air supply rate is higher. This tendency can be found in the cases of carbon dioxide and in the case of formaldehyde.

Figure 30 and 31 show the averages of concentrations in the week. The figure shows the maximum and minimum of hourly average too. If the target concentration is lower, the average concentration is also lower. The maximum concentration in the case of an exhaust system is higher than that in the case of a supply and exhaust system.

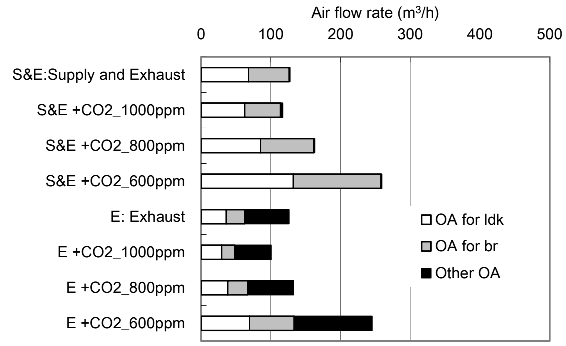

Figure 28 Averages of outside air supply rates in houses with/without CO_2 sensor

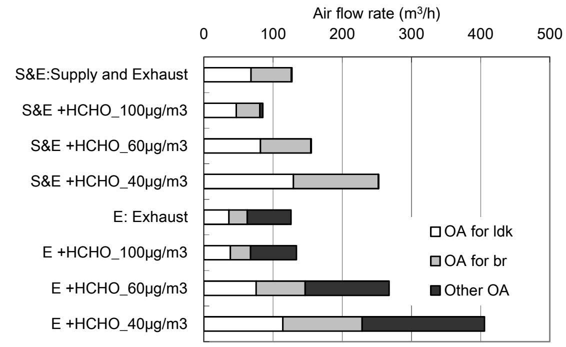

Figure 29 Averages of outside air supply rates in houses with and without HCHO sensor

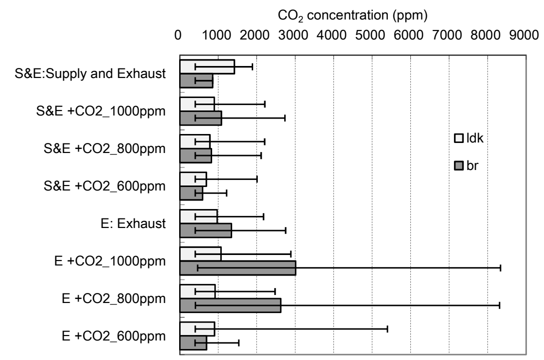

Figure 30 Average, maximum and minimum of CO_2 concentration in houses with/without CO_2 sensor

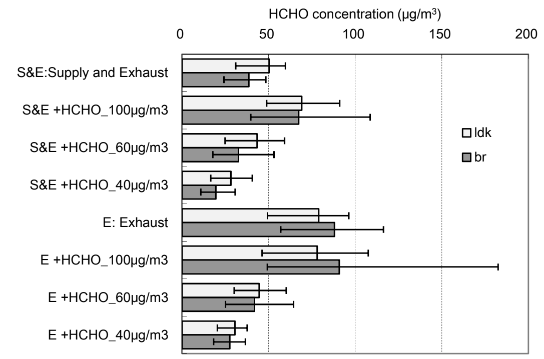

Figure 31 Average, maximum and minimum of HCHO concentration in houses with/without HCHO sensor

CONCLUSION

The simulation program: 'Fresh' is improved in order to predict the effect of hybrid ventilation systems with concentration sensors. The simulation includes the considerations on the influences of dwellers' behaviour and the leakage network of detached house. Therefore, the results describe the real effect of the composed ventilation system in real houses.

The simulation results showed that the control of indoor concentration in summer is difficult for the system with a sensor at an exhaust stack, because the dwellers' behaviour of opening windows influences the ventilation routes. In winter, the control with a concentration sensor is effective in keeping the indoor concentration low and in decreasing ventilation rate and the energy loss with ventilation.

NOMENCLATURE

h(t)= the initial response of thermal-flow rate

B_0= the steady value of thermal-flow rate

δ (t)= Delta function

q = the airflow rate

n= the exponent of airflow friction

[D]= the matrix of airflow friction

[K]= the matrix of room air elasticity

{Fwind}= the power of wind

{Ftemp}= the power by the room air density

[Q]= the matrix of airflow rate

Q(i,j)= the airflow rate from room-i to room-j

C(t)= the concentration of a pollutant

[V]= the volume of a room

{M}= the emission rate of a pollutant in each room.

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