SIMULATION OF VENTILATION AND INDOOR AIR QUALITY IN HOUSES USING AVERAGE JAPANESE DAILY SCHEDULE

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ABSTRACT

In order to explain the effect of ventilation systems and airtight performance of houses in detached houses, the investigation was made on a simulation program which calculates the ventilation rates and indoor air quality. The ventilation rates and the concentrations of CO_2 , CO and formaldehyde in general Japanese houses with three kinds of ventilation systems were calculated through a year in three cities of Japan. The results of the simulation showed a case in which the concentrations of the pollutants are not acceptable. And the performance of the ventilation system and the solution method of realizing these ventilation systems were discussed on the basis of the results of the simulation.

INTRODUCTION

With the elevation of demand level for thermal comfort and energy saving, the airtight level of general Japanese houses has become higher but IAQ problem has emerged. In order to keep IAQ in general houses, it is necessary to make a guideline of ventilation and materials considering the fluctuation of the concentration of pollutants caused by the factors such as ventilation rates and emission rates. The factors are influenced by heating, cooling, ventilation, opening windows, the characteristics of emission from people and materials and thermal performance of houses. And, it is necessary to predict the fluctuation of IAQ in general houses on the basis of the average Japanese daily shchedule and the standerd weathor data especially for keeping indoor air quality in airtight houses.

METHODS

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

[Dynamic thermal calculation of the tempertature, heating and cooling loads] The calculation method was devised by Dr.Aratani, Hokkaido Univercity in 1974. The inditial responses of the thermal-flow rates are calculated and the functions of the responses are described as the following equation in order to increase the speed of the calculation.

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

Where, $h(t)$ the inditial response of thermal-flow rate, B_0 the steady value of thermal flowrate, $q = \Sigma B_m / \beta_m$ 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 calculated temperatures in the other rooms and the calculated vantilation rates as the values Δt before. In the following case studies, the interval time Δt was decided 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. And the thermal loads with the human behaviors such as cooking, watching television and cleaning rooms, are calculated from the daily schedule model of a family. The air-conditioning and the windows are operated to make the indoor climate comfortable considering the daily schedule of the family. The air-conditioning systems and the windows are controlled as follows in the following case studies.The room temperatures are controlled to be above 22 C by heating in huses with a central heating system. The room temperatures are controlled to be above 22 C and below 28 C by opening windows in houses with a central heating system. The room temperatures are controlled to be below 28 C by cooling.

[Calculation of air flow rate in the multi-cell system using the equation of the power at the openings] The airflow rates are calculated using the following equations which are made from the balances of power at openings.

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

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 New mark'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 the wind pressure, the ratio of wind speed considering the circumstances and the performance of the fans. In the case of the following studies, the ratios of wind speed at the town to the speed at the plain flat ground was 0.3.

[Dynamic calculation of concentration of pollutants using the equation of the amount of pollutants] The concentrations of pollutants in each room are calculated using the following equations which are made considering the balance of the volume of the pollutants.

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

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 concentrations of a pollutant, *[V]* the volume of rooms, *{M}* the emmission rates of a pollutant in each room.

The equations can be solved using New mark's numerical integration method. The emission rates of CO_2 and CO are calculated using the average Japanese daily schedule and the data on the emission rates caused by the people's behavior in houses shown in Table1. The daily schedule of each family in a house is calculated considering the plan of the house using the results of the survey on the Japanese daily schedule by NHK. Figure2 shows the calculated emission rates of CO_2 and CO on holiday and weekday in the house model. The emission rates of

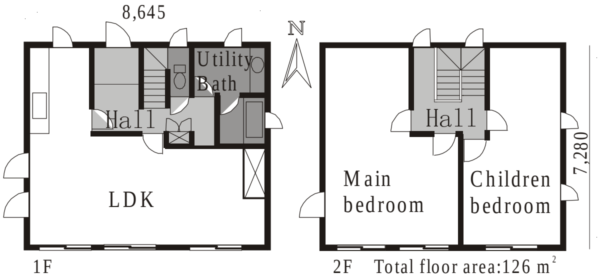


Figure1 The plan of detached house model

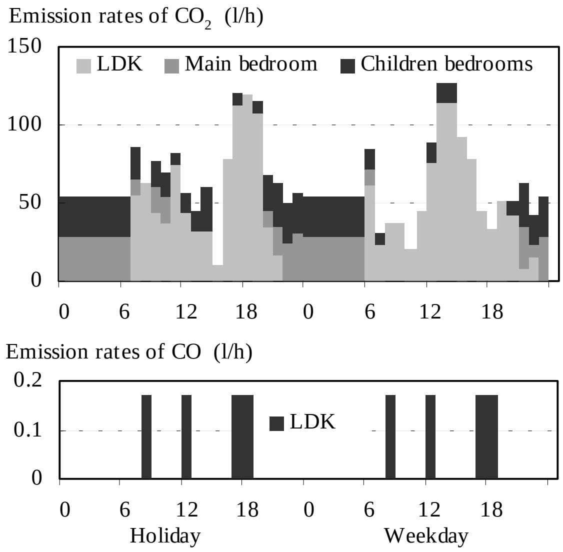


Figure 2 The calculated emission rate of CO_2 and CO

CO_2 change with the behavior of the family and 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 general Japanese detached houses. The emisson rates of CO are calculated considering the performance of the hood and the gas range as shown in Figure 2.

The emission rates of folmaldehyde are calculated

Table 1 Emission rate of CO_2 from the standerd Japanese dwellers

Behavior	place	Man_ worker	Woman_ house keeper or junior high school student	High shool student	Gas range 3 KW
Eating	Dinig room	20.5	18.4	20.8	
Cooking	Kitchen	31.5	28.3	32	26.4
Watching TV	Living room	17.2	15.5	17.5	
Hobbies and Game	Living room	26	23.4	26.4	
Reading news paper	Living room	20.5	18.4	20.8	
Talking	Living room	20.5	18.4	20.8	
Listening to the radio	Bed rooms	17.2	15.5	17.5	
Washing	Utility,Bath	26	23.4	26.4	
Sleeping	Bed rooms	15	13.5	15.3	
Bathing	Utility,Bath	20.3	18.2	20.6	
Reading books	Living room	17.2	15.5	17.5	
Cleaning	every room	37	33.2	37.6	

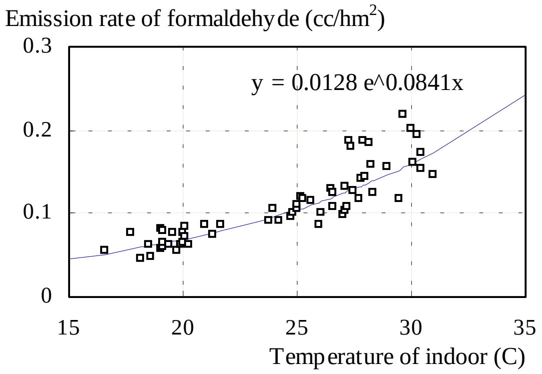


Figure 3 the measured emission rate of formaldehyde in the general detached house constructed in 1995.

from the data of the measurement in a house and the calculated temperature. In the following case studies, the measured emission rates and the characteristics to the temperature shown in Figure 3 were used. The emission rates were measured in a genaral japanese detached house in Kyoto prefecture constructed in 1995. The measurements were made from April to December in 1998. The ventilation rates were measured using the constant injection method with R-22 as a tracer gas. The continuous formaldehyde analyzer with a reagent which contains acetylacetone was used and the concentration was measured twice an hour. The emission ratea were calculated from the measured ventilation rates and the measured concentrations. The emision rates increase with indoor temperature as shown in Figure 3. The approximate equation of formaldehyde emission rate is shown in Figure 3.

SIMULATION MODELS

In order to explain the characteristics of ventilation systems in the general Japanese houses, three types of ventilation systems are designed in a standard Japanese detached house model shown in Figure 1. Type-1 is the passive ventilation system using openings and leaks of houses. Type-2 is the passive stack ventilation system using a stack and a pre-heat air supply opening. Type-3 is a central mechanical ventilation system with heat recovery unit. The passive ventilation has been used in general houses in the mild region of Japan. The stack ventilation system has been investigated since 1992 in the cold region of Japan. In houses using above these ventilation systems, the fresh air is led to the rooms on the first floor and the air is led to the rooms on the second floor through the stairwell. The air which is led to the rooms on the second floor is the used air which comes from the rooms on the first floor. The patterns of the change of the concentrations in the rooms are not same as those in the houses where the used air is not led to the rooms. In the houses using the central mechanical ventilation system which consists of ducts, an air supply fan and an exhaust fan, the fresh air is supplied to the rooms and the air is exhausted constantly from the dirty zone, toilet, bath and kitchen. The designed performances of these ventilation systems are shown in Table 2. The air flow ratios of openings in the house with type-1 were decided on condition that the total air change rate of the house meets 0.5 times per hour when the temperature difference is 20 (k). The air flow ratios of the stack and the air supply opening in the house with type-2 were decided on condition that the total air change rate of the house meets 0.5 times per hour when the temperature difference is 20 (k). And the airflow ratio of the ducts from the rooms to the stack were decided on condition that the airflow rates meet the ventilation requirements : 20 $m^3/(h \cdot person)$. And in the house with type-3, the air supply rates were decided to meet the ventilation requirement on condition that the total air change rate of the house meets 0.5 times per hour . The equivalent leakage area per its floor area of the houses are 2 cm^2/m^2. The airtight level is the same as the latest Japanese standard for the airtight houses. The temperature, the thermal loads, the ventilation rates, the ventilation routes, the concentrations of pollutants in the standard house shown in Figure 1 using the above ventilation systems were calculated using the simulation program 'Fresh96' with the standard

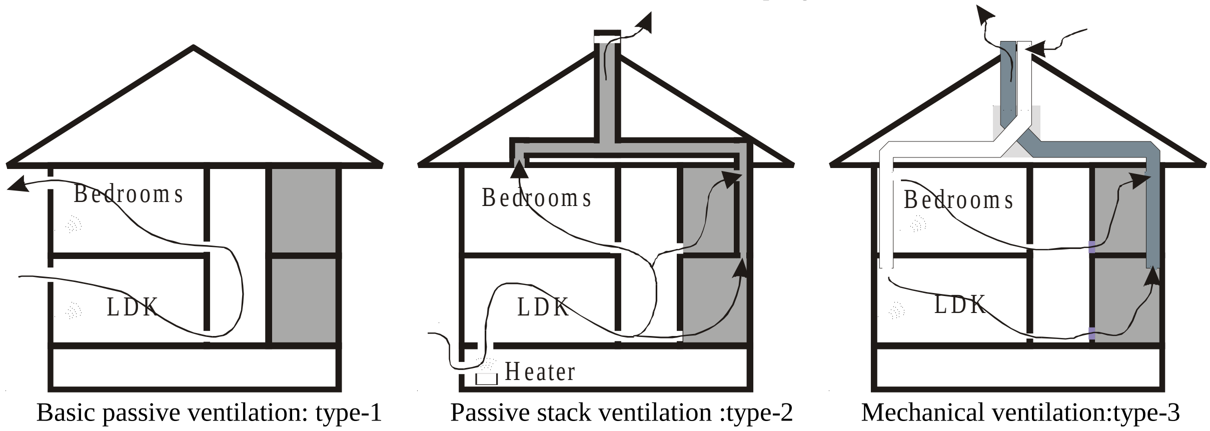


Figure 4 The ventilation systems in the house model

Table 2 the designed performance of the ventilation systems

Children bedroom	Airflow rates (Equivalent opening area [Exponent of airflow])		
type	type-1 Basic passive ventilation	type-2 Passive stack ventilation	type-3 Mechanical ventilation
Living & Dining & Kitchen	600 cm^2 [N=1]	the airflow ratio of stack is 352 m^3/hmmAq$^{1/1.5}$ and the height of stack is 12m. The air is exhaust from the bedrooms and Toilet & Bath room.	80 m^3/h supply
Main bedroom	300 cm^2 [N=1]		40 m^3/h supply
Children bedroom	300 cm^2 [N=1]		40 m^3/h supply
Hall	120 cm^2 [N=1]		-
Toilet & Bath room	120 cm^2 [N=1]		160 m^3/h exhaust
	The airflow rate of range hood is 350 m^3/h. The total airflow rate of Toilet and Bathroom is 100 m^3/h. These fans are used when the dweller uses the room.		The airflow rates are constant.

weather data of Sapporo, Tokyo and Kagoshima.

RESULTS

Figure 5 shows the monthly averages of the calculated ventilation rates and the ventilation routes in the house with type-2:passive stack ventilation and type-3:mechanical ventilation. In the case of type-2, the fresh air is led to LDK on the first floor through the air-supply openings and the air flows up to the bedrooms on the second floor through the stairwell. The fresh air infiltrates to every room and the infiltration to the rooms on the second floor is asumed to be caused by the wind pressure. The ratio of the air-supply rate through the designed routes to the total ventilation rate was 56%. The dirty air in kitchen was exhausted by the fan when a dweller uses the gas range and the monthly averages of the rate was 15.9 m^3/h. The total ventilation rate of the house was almost 180 m^3/h in January and the rate was larger than the ventilation requirement. But, in the case of type-1 and type-2, the concentrations of the pollutant in the room on the second floor will be heigher than that on the first floor. In the case of type-3, the fresh air is led to every room. And the air is led to the toilet and the bathroom through the hall and the stairwell. So the designed ventilation routes are almost realized, but the air exfiltrated to the outside in the bedrooms on the second floor. The ratio of the air-supply rate through the designed routes to the total ventilation rate was 72%.

Figure 6 shows the daily change of the ventilation and the concentration of pollutants on 1-January in

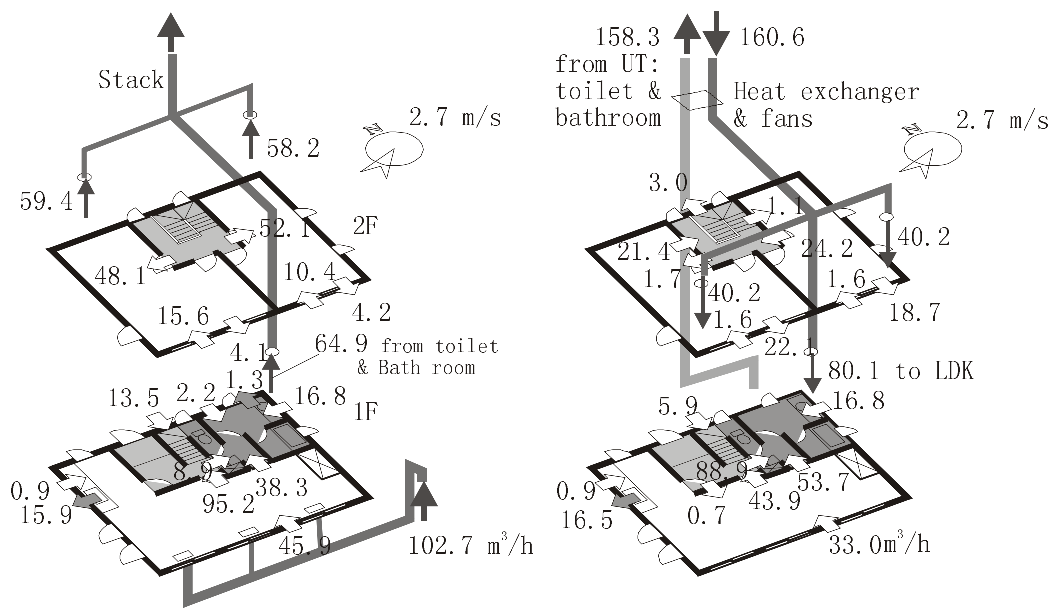
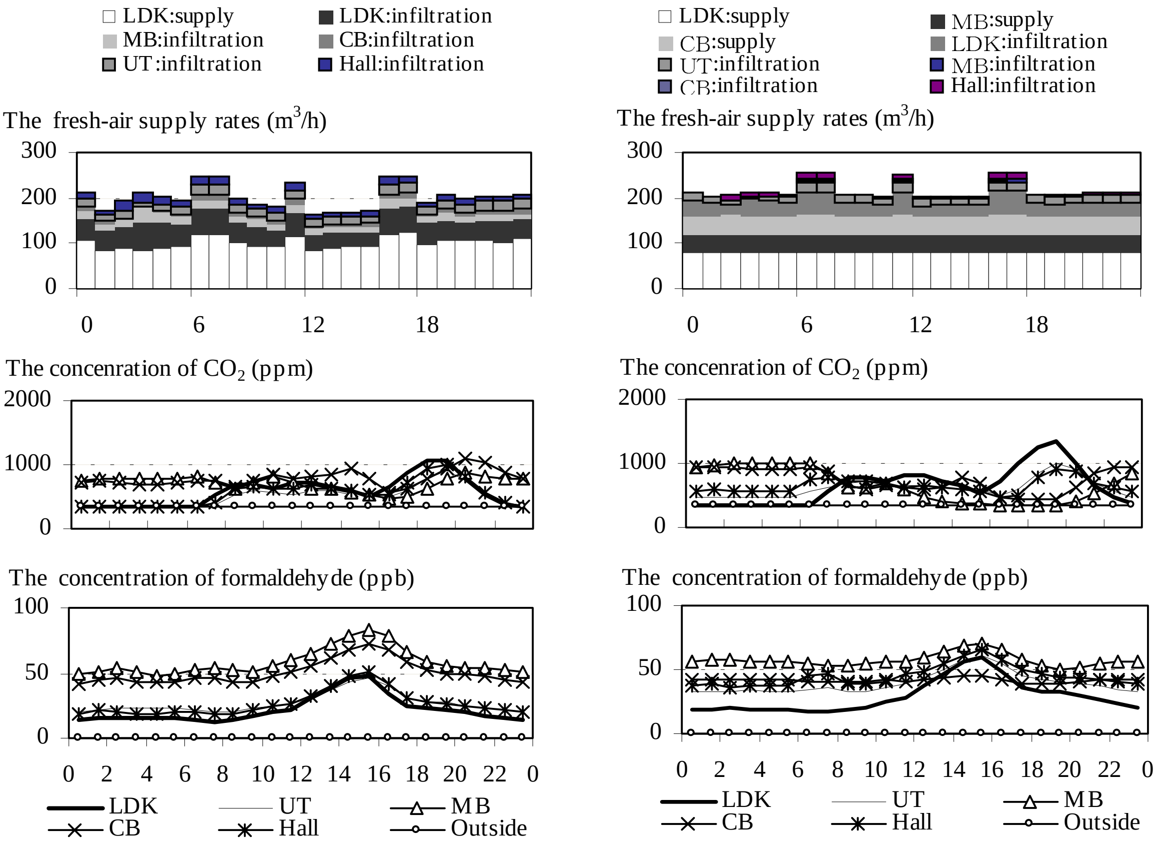


Figure 5 the calculated airflow rates in the house with type-2 and type-3 (the average airflow rates in January)



Type-2 on 1-January in Sapporo

Type-3 on 1-January in Sapporo

Figure 6 The daily change of the ventilation rates and the concentrations of the pollutants

the houses with type-2 and type-3. The ventilation rates of type-2 were almost same as those of type-3, but the fresh air supply rates to each room was not same. In the case of type-2, the most of the fresh air was led to the rooms on the first floor. In the case of type-2, the fresh air is led to all rooms. The peek of the concentrations of CO_2 weas 1100 ppm in the house with type-2 and 1300 ppm in the house with type-3. The concentration changed with the emission rates. The concentrations in the bedrooms were high at night. And in the case of type-2, the concentrations in the bedroom were also high at daytime, but in the case of type-3 those were not heigh at daytime, because the rate of the airflow which is led to the bedrooms from LDK was low. The peeks of the concentrations of CO were almost 1 ppm and the peeks were highest at the dinner time (18:00). In the case of type-2, the concentrations in Hall were almost same as those in LDK, and those in the bedrooms were almose half of those in LDK. In the case of type-3, the concentrations in th ebedrooms were low. The concentrations of formaldehyde changed with the indoor temperatures. In the case of type-2, the concentrations in the bedrooms were higher than those in LDK all day. But in the case of type-3, the concentrations in LDK were almost same as those in th bedrooms in the afternoon. The daily averages of the concentration when people use the rooms were 40 ppb in the two cases. The results from the simulation in the house with type-1 were almost same as those in the house with type-2.

Figure 7 shows the standerd weather data 'HASP' of Sapporo. And figure 8 shows the yealy change of the ventilation rates, and the concentrations in th ecase of type-2. The concentrations in the house with the passive ventilation systems, will be higher when the temperature difference is small and the ventilation rate is low. So, the simulations through the year are necessary for these ventilation methods. In Sapporo, the temperature difference will be smaller than 20 (k) from April to October. In summer, the concentrations will not be higher because the windows are opened in the house without cooling systems. So the risk of indoor air problem will be highest in spring and autum when the dwellers don't open windows usually.

Figuer 8 shows the yearly change of the ventilation rates and the concentrations when the indoor temperature will be heigher than 26C and the dwellers open the windows. The ventilation rates increased with the temperature difference and wind pressure. And the rate was very high on the hot day because the windows were opened. The concentrations were heigh from spring to autumn with the exception of the hot days in summer. These yearly characteristics of the concentrations were shown in the case of type-1. The height of the peeks of CO was steady through the year with the exception of the height on the hot days because the height were mainly influenced by the volume of the rooms. The concentrations of formaldehyde were high from spring to autumn with the exception of the hot days in summer, because the emission rates became higher with the indoor temperature. In the case of type-3, the ventalation rates were steady and these risks from spring to autumn are lower than those in the case of the passive ventilation systems. But the concentrations of formaldehyde were higher in these heigh risk seasons than those in the other seasons because of the heigh indoor temperature.

Figure 9 shows the change of the monthly average of the ventilation rates and the concentrations when dwellers use the room in the houses with type-2 in Tokyo, type-2 and type-3 in Sapporo. The ventilation rates were devided into two parts in the figure. One is the average of the ventilation rates when the windows are opened and another is the raverage of those when the windows are closed. In the case of type-2 in Tokyo, the ventilation rates are lower than the ventilation requirement in most seasons. The ventilation rates were very low when the windows are closed and the rooms are cooled in summer. And the concentrations of formaldehyde were very high in the season. The designd airflow ratios of the stacks and the openings must be changed. In the case of type-2 in Sapporo, the ventilation rates become low in May and September, and the concentrations has two peeks in these months. In the case of type-1 in Sapporo, the ventilation rate in September was lowest and the concentrations become highest in September. So the concentrations in the

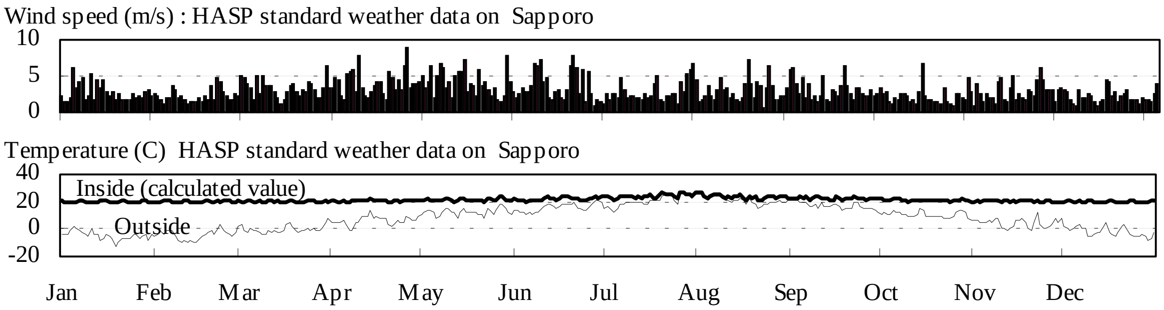


Figure 7 The HASP standerd weather data of Sapporo

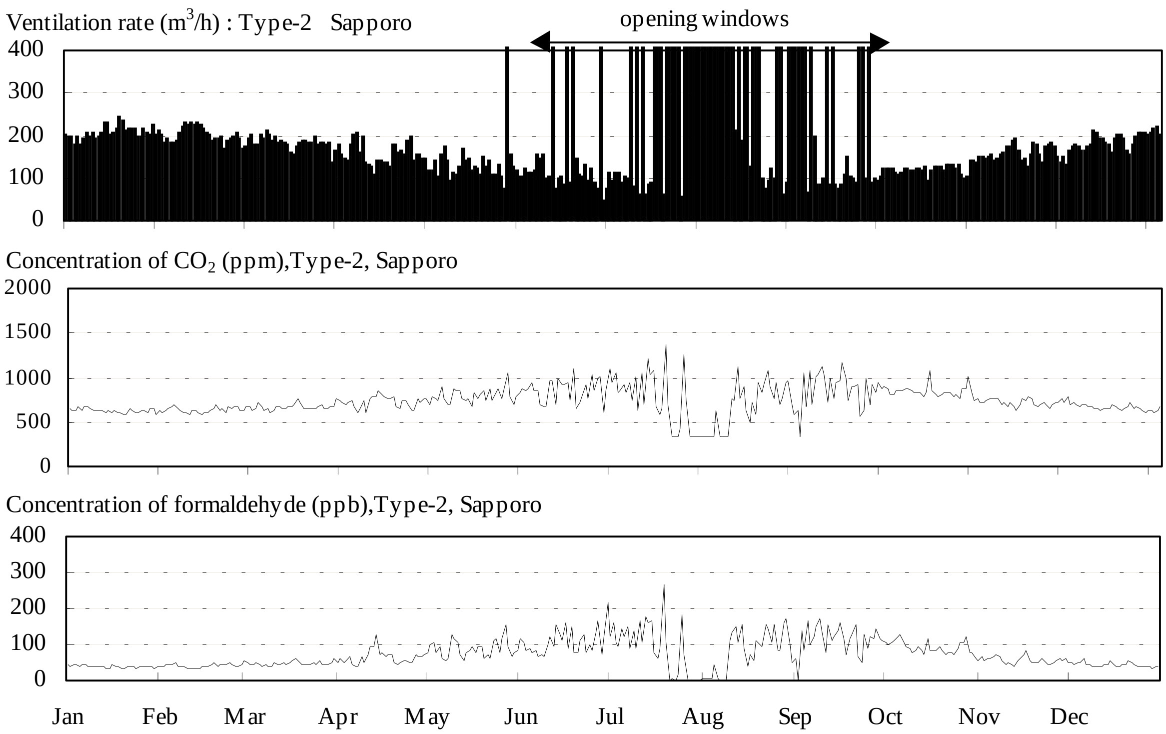


Figure 8 The yearly change of the ventilation rates and the concentrations of the pollutants

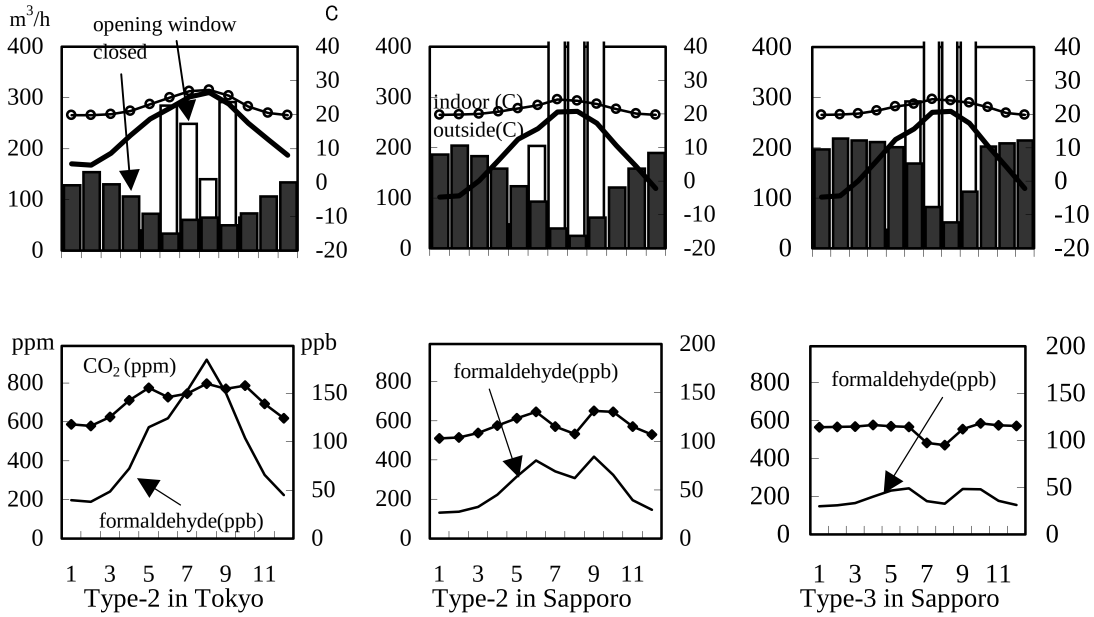


Figure 9 The monthly change of the ventilation rates, the temperatures and the concentrations

house with the passive ventilation systems will be acceptable if the dweller open the small windows for ventilation or use the fans in these seasons. In the case of type-3, the ventilation rate was steady with the exception of the months when the windows are often opened. The concentrations were almost steady, but the concentrations became lower in summer by the effect of opening windows.

Table 3 shows the performances of the ventilation systems in the three cities. The yearly average ventilation rates when the windows are closed are 94-209. The average rates in the case of type-1 were lowest and those of type-3 were highest. In the case of type-1 and type-2, the average rates were lower than the ventilation requirement. The results show that the air flow ratios of the ventilation routes must be designed considering the yealy change of the temperature difference and the wind pressure in the house with passive ventilation systems. The ratio of the number of days when the average of the air change rate is larger than 0.35 was 100% in the case of type-3, but that of type-2 was 59-84% and that of type-1 was 33-72%. The ratio in the case of the passive ventilation systems was high in Sapporo in the cold region, because the length of the high risk season is short. In Sapporo, the dwellers does not use cooling systems. The cooling systems are used in Tokyo and Kagoshima. The ratios in Tokyo were a little lower than those in Kagoshima. Because the wind speed in Kagoshima is higher than that in Tokyo and the length of the season when cooling is necessary was shorter in Kagoshima than in Tokyo. The trend was shown on the ratios of the number of days when the average of the air change rate is larger than 0.5. The ratios of the time when the concentrations of CO_2 is lower than 1000ppm were 82-98%. The deviation of these ratios was lower than that of the ratios of number of the days. The averages of the concentration when dwellers use the room were 451-704ppm. That in the case of type2 in Tokyo was the highest. The averages of the concentration of CO when dwellers use the room were 0.05-0.17 ppm. That in the case of type2 in Tokyo was the highest. The averages of the concentration of formaldehyde when dwellers use the room were 33-95 ppb. That in the case of type2 in Tokyo was the highest. Though the ventilation rates in th e vcase of type-2 were higher than those of type-1, the concentrations in the case of type-2 were higher than those on type-1. The reason was asumed to be based on the ventilation routes. In the house with type-1, most of the air is led to the bedrooms from Hall. But in the case of type-2, 30% of the air is led to UT:Toilet and Bathroom. So the airflow rates through the bedrooms were lower in the house with type-2 than those in the house with type-1. In the house with type-1, the dirty air flows back to Hall and the rooms when dwellers do not use UT and the fan is not used.

CONCLUSIONS

These results show that the performances of the houses, the performances of the ventilation systems, the ventilation design and the weather influence upon the yearly characteristics of the ventilation and the indoor air quality. So, it is necessary to use simulation techniqes for designing the ventilation in the airtight houses. And the simulations through the year are necessary to investigate the passive ventilation systems.

Table 3 The performances of the ventilation systems (type-1,type-2,type-3)

	Ⅰ:Sapporo			Ⅳ:Tokyo			Ⅴ:Kagoshima		
	type-1	type-2	type-3	type-1	type-2	type-3	type-1	type-2	type-3
The yearly average of the ventilation rates when the windows are closed [m3/h]	134	153	209	94	111	201	94	115	201
The ratio of number of days when the average of the air change rate is heiger than 0.35 [%]	72 %	84 %	100 %	***33 %***	***59 %***	100 %	***37 %***	68 %	100 %
The ratio of number of days when the average of the air change rate is heiger than 0.50 [%]	***42 %***	58 %	100 %	***17 %***	***26 %***	100 %	***19 %***	***39 %***	100 %
The ratio of the time when the concentration of CO2 is lower than 1000ppm [%]	96 %	92 %	98 %	88 %	82 %	98 %	88 %	89 %	98 %
The average of the concentration when dwellers use the room (ppm)	451	576	555	576	704	566	554	578	564
The average of the concentration of CO when dwellers use the room (ppm)	0.05	0.11	0.08	0.11	0.17	0.08	0.1	0.11	0.08
The average of the concentration of formaldehyde when dwellers use the room	33	52	38	69	95	45	69	58	48

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NOMENCLATURE

$h(t)$: the inditial response of thermal-flow rate

B_0: the steady value of thermal-flow rate

$\delta(t)$: Delta function

q : the airflow rate

n: the exponent of airflow friction

$[D]$: the matrix of airflow friction

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$\{F_{wind}\}$: the power of wind

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$[Q]$: the matrix of airflow rate

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

$C(t)$: the concentrations of a pollutant

$[V]$: the volume of rooms

$\{M\}$: the emmision rates of a pollutant in each room.