原　著

# Seasonal Change of Ventilation and IAQ in Houses with Hybrid Ventilation Systems

Motoya HAYASHI*

This paper presents the results of investigations that were made on a simulation program, which calculates the temperature, the heat loads, the ventilation rates and the indoor air quality considering Japanese daily schedule and the dweller's behavior toward keeping comfortable indoor climate, in order to explain the effect of ventilation systems. In the investigation, the concentrations of carbon dioxide, carbon monoxide and formaldehyde are regarded as indicators of indoor air quality. Firstly three types of systems were designed in a house model. They were a mechanical ventilation system, a passive ventilation system and a hybrid ventilation system. Next, the simulation was performed using the standard weather data in Japan. And the simulation made clear the seasonal characteristics of ventilation and indoor air quality and the advantages of the hybrid ventilation systems.

## 1.Introduction

With the elevation of demand level for thermal comfort and energy saving, the airtight level of general Japanese houses has become higher but indoor air quality problem have emerged. One of the reasons is that most residents in Japan don't recognize the need of ventilation, because the natural ventilation through the leaks has prevented indoor air pollution in general houses for a long time. Another reason is thought to be the increase in the use of the building materials which contain chemical compounds. The concentrations of pollutants in rooms mainly depend on the ventilation rates and the emission rates. They were influenced by many factors: heating, cooling, opening windows, ventilation systems, the characteristics of emission from dwellers and building materials, thermal performance of houses and the weather condition. Weather conditions in Japan vary a lot, but the most efficient system for the region is not necessarily used though there are various ventilation systems now in use. So, it is necessary to predict the seasonal characteristics of indoor air quality in general houses, especially for keeping indoor air quality in airtight houses.

**Table 1 Nomenclature**

| | |
|---|---|
| $h(t)$ the inditial response of thermal-flow rate | $B_0$ the steady value of thermal-flow rate |
| $\delta(t)$ Delta function | $\{F_{temp}\}$ the power by the room air density |
| $q$ the airflow rate | [Q] the matrix of airflow rate |
| $n$ the exponent of airflow friction | Q(i,j) the airflow rate from room-i to room-j |
| [D] the matrix of airflow friction | $C(t)$ the concentrations of a pollutant |
| [K] the matrix of room air elasticity | [V] the volume of rooms |
| $\{F_{wind}\}$ the power of wind | {M} the emmision rates of a pollutant in each |

## 2. Methods

The author's simulation program was written in 1996, and was named Fresh. And it was improved in 2003. It is composed of the following three calculation methods.

### 2.1 Dynamic thermal calculation of heating and cooling loads and temperatures

In the calculation method, the indicial responses of the thermal-flow rates through the heat boundary layers such as outer walls, inner walls, floors, ceilings and windows, are first calculated and the functions of the responses are described as the following equation in order to speed up the calculation.

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

Where, $h(t)$ the indicial response of thermal flow rate, $B_0$ the steady value of thermal flow rate, $q=\sum(B_m/\beta_m)$ and $\delta(t)$ Delta function. The temperatures and the heating and cooling loads are calculated with the above equation using Duhamel's integration method in consideration of a heat balance of each room.

* Department of Life Style and Space Design, MiyagiGakuin Women's University, Japan

The temperatures and the heating and cooling loads are also calculated using the calculated temperatures in the other rooms and the calculated ventilation rates as the values $\Delta t$ before. In the following case studies, the interval time $\Delta t$ was decided to be 5 minutes. This value assures satisfactory calculation precision. The values are calculated using the standard weather data from Society of Heating, Air-conditioning and Sanitary Engineers of Japan. The rates of the solar radiation through the windows are calculated considering the effect of shades and the shadow of the neighbouring buildings. And the thermal loads with the human behaviours such as cooking, watching television and cleaning rooms, are calculated from the daily schedule models of a family on holiday and weekday. The air-conditioner 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 the marginal seasons and summer, the room temperatures are controlled to meet 26 °*C* by opening windows. The dwellers in the rooms make the operation of the windows. When the effect of the operations is insufficient, the room temperatures are controlled to be below 28 °*C* in houses with a cooling system. As a result, the temperatures in the rooms with the dwellers are above 22 °*C* and below 28 °*C* through the year in houses with cooling and heating systems.

**2.2 Calculation of airflow rates in the multi-cell system**

The airflow rates are calculated using the following equation, which is made from the balances of power at openings.

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

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 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 wind pressure coefficient, 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 0.3 and the wind pressure coefficient: C was set up as follows by the angle: $\omega$. C =0.75 ($\omega$<=30), -0.01857$\omega$+1.3125 (30<$\omega$<70),-0.02$\omega$+1.4 (70<=$\omega$<90) ,-0.4 (90<=$\omega$).Where, $\omega$(degree) the angle that the direction which is vertical to the wall side and the one for the wind make it. The coefficient of the roof side is the same as the leeward wall. And the coefficient of the floor in the first floor is zero.

**2.3 Dynamic calculation of concentrations in the multi-cell system**

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]{C(t)}+[V]{C'(t)}={M(t)}. Where [Q] the matrix of airflow rate, Q(i,j):the airflow rate from room-i to room-j, Q(k,k) the negative value of the total airflow rate from room-k, C(t) the concentration of a pollutant, [V] the volume of rooms, {M} the emission rate of a pollutant. The equations can be solved using New-mark's numerical integration method. The emission rates of carbon dioxide and carbon monoxide are calculated using the Japanese daily schedule and the data on the emission rates caused by the dweller's behavior in houses shown in Figure 1. 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. Figure 2 shows the calculated emission rates of carbon dioxide and carbon monoxide on holiday and weekday in the house model. The emission rates of carbon dioxide 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 carbon dioxide in general Japanese detached houses. The emission rates of carbon monoxide are calculated considering the performance of the hood and the gas range as shown in Figure 2.

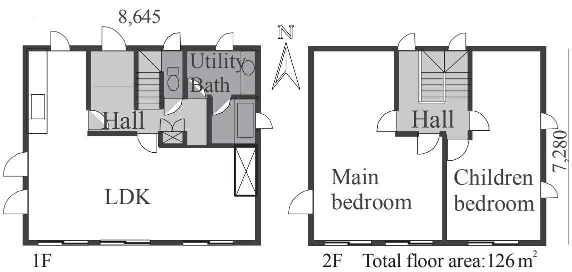


**Figure 1 Plan of a detached house model**

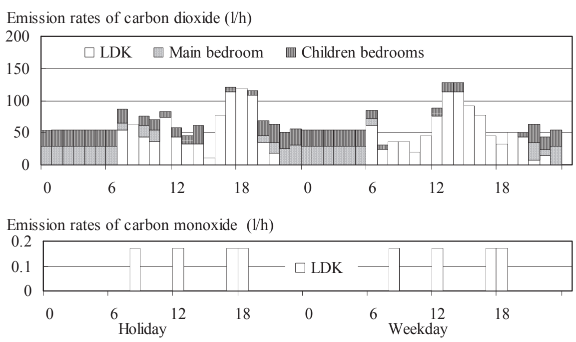


**Figure 2 Calculated emission rates of carbon dioxide and carbon monoxide**

The emission rates of formaldehyde were calculated using an equation. The influences of temperature and sink were considered in the equation.

$$E = E_{25} \cdot a^{(T-25)} - \beta \cdot C(t) \qquad (3)$$

Where E emission rate($\mu$g/h㎡), $E_{25}$(=100[$\mu$g/h㎡]) :emission rate measured in small chamber when temperature is 25degC, T: temperature, $\beta$(=0.06):ratio of sink measured in small chamber, C(t):concentration[$\mu g/m^3$]

In the studies, the concentrations on outside were set as follows. The concentration of carbon dioxide is 400ppm and that of carbon monoxide is 0 ppm and that of formaldehyde 0 ppb.

### 3.Simulation Models

In order to explain the seasonal characteristics of ventilation systems, three types of ventilation systems are designed in a standard Japanese detached house model shown in Figure1. In the houses using above these ventilation systems, the fresh air is led to the rooms on the second floor and after that to LDK, toilet and bath room on the first floor through the stairwell in the hall as shown in Figure 3.

The designed performances of these ventilation systems are shown in Table 2. In the house with the active ventilation system, the air supply rates were decided to meet the ventilation requirement on condition that the total air change rate of the house is 0.5 times per hour. The airflow ratios of the stack in the house with the passive ventilation system and in the house with hybrid ventilation systems were decided on condition that the total air change rate of the house meets 0.5 times per hour when the difference between indoor and outdoor temperature is 20 degrees. The equivalent leakage area per its floor area of the houses is 0.5 $cm^2/m^2$. The temperature, the thermal loads, the ventilation rates, the ventilation routes, the concentrations of pollutants in the standard house using the above ventilation systems shown in Figure 3 were calculated using the simulation program Fresh2003 with the standard weather data of Tokyo: north latitude 35.7.

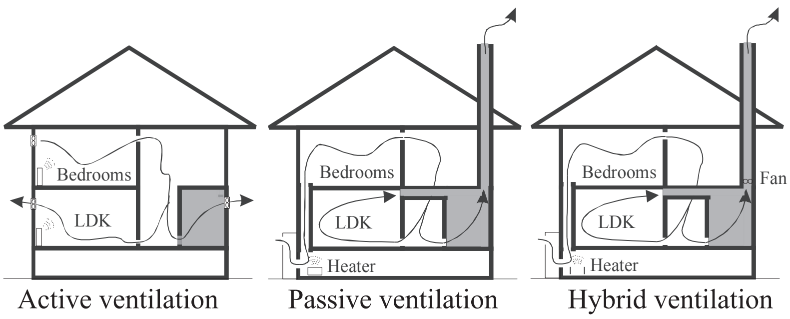


**Figure 3 Designed ventilation systems**

**Table 2 Performances of the designed ventilation systems**

| Airflow rates (Equivalent opening area [Exponent of airflow]) | | | |
|---|---|---|---|
| Types | Active ventilation | Passive ventilation | Hybrid ventilation |
| Living & Dining & Kitchen | 100 $m^3$/h exhaust | The airflow ratio of stack is 300 $m^3/hmmAq^{1/1.8}$ and the height of stack is 9.5m. The airflow ratio of air supply route is 300 $m^3/hmmAq^{1/1.8}$ and the height is 0.5m. | The air flow rate was controlled to meet 150 $m^3$/h using a fan. |
| Main bedroom | 75 $m^3$/h supply | | |
| Children bedroom | 75 $m^3$/h supply | | |
| Toilet & Bath room | 50 $m^3$/h exhaust | | |

### 4. Results

Figure 4 shows the standard weather data HASP on Tokyo. In the simulation, the data on the outdoor temperature, the solar radiation, the wind speed and the wind direction were used.

Figure 5 shows the seasonal change of air change rates in the whole house. In the house with active ventilation system, the air change rates were almost 0.5(1/h) when the windows were closed, but the air change rate increased when the windows were opened to make indoor climate comfortable.

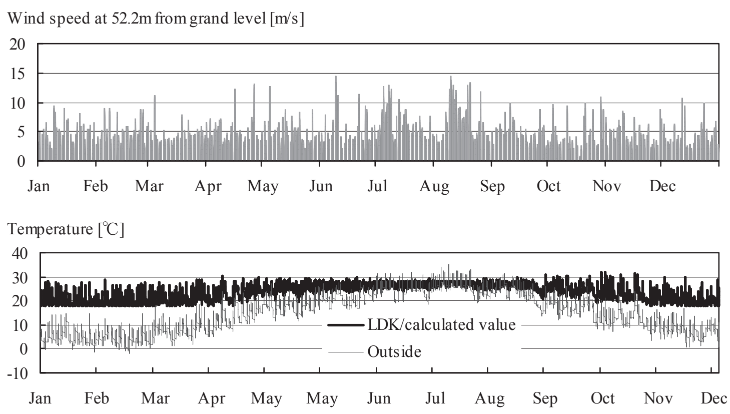


**Figure 4 HASP standard weather data on Tokyo**

In the house with the passive ventilation system, the air change rate changes from 0 to 0.6(1/h) in accordance with the difference between indoor and outdoor temperature when the windows are closed. In summer, the air change rate was very low when the cooling unit was operated.

In the house with the hybrid ventilation system, the air change rates were 0.5 to 0.6(1/h) when the windows are closed. The air change rate was controlled to meet 0.5(1/h) with a fan and an airflow sensor in the simulation.

Figure 6 shows the monthly averages. The indoor temperature changed from 21 to 26 C in the houses with three types of ventilation systems. The rate of the number of days when the windows are closed all time changed 0 to 100%. In the three months in winter, the windows were not opened at all, and in July, the windows were opened every day. From June to September, the cooling units were used. And in May, Both of the heating unit and the cooling unit were not used. The rates in the houses with the hybrid ventilation system were high in April, because the air changed through the designed ventilation routes with the passive effect and the indoor temperature did not increase. The rates in the house with the passive ventilation system were not low because of the same characteristics.

The concentrations in Figure 6 were the monthly averages of the concentrations in the rooms when the windows are closed. In the house with the passive ventilation system, the concentrations increased from winter to spring. It was due to the decrease of the air change rate. And the concentrations decreased in early summer because the windows were opened. The concentration increased in summer because the windows were closed with cooling systems operating. And the concentrations decreased in autumn. In the house with the other ventilation systems, there were not the same changes in summer. But in the houses with the active ventilation system or the hybrid ventilation system, the concentrations in mild seasons were lower than those in winter. The reason was thought to be that opening windows makes the concentrations in the closed time lower. The concentrations of carbon dioxide: $CO_2$ when the windows were closed were higher in the house with the passive ventilation system than in the other houses. The differences were larger from spring to fall because the air change rate decreased in the house with passive ventilation system in these seasons. The difference was the highest in August when the cooling unit was used long. The concentrations of carbon monoxide: CO when the windows are closed had the same seasonal characteristics as those of $CO_2$. The concentration of formaldehyde: HCHO has also the same seasonal characteristics.

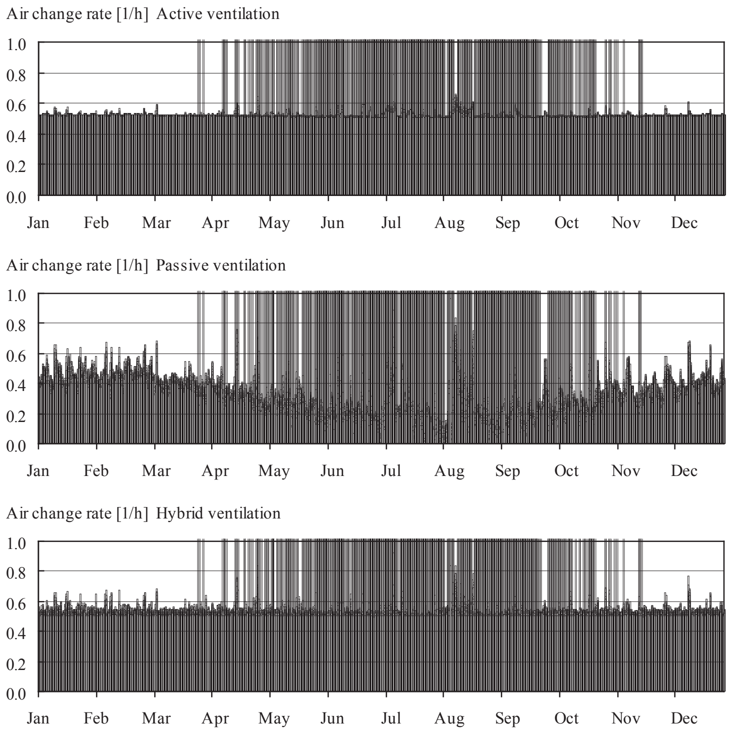


**Figure 5  Seasonal change of air change rate**

Figure 7 shows the comparison concerning the indoor air quality and heat losses with ventilation. The peaks of these concentrations in the house with passive ventilation systems were very higher than those in the house with the other ventilation systems. The average concentrations in the rooms when the people use in the house with passive ventilation systems were higher than those in the house with the other ventilation systems. And the concentrations in the house with the hybrid ventilation system were almost the same as those with active ventilation system. The heat loss with ventilation in the house with the passive ventilation was the lowest because the air change rates were the lowest. The heat losses with hybrid ventilation were 107% of those with active ventilation.

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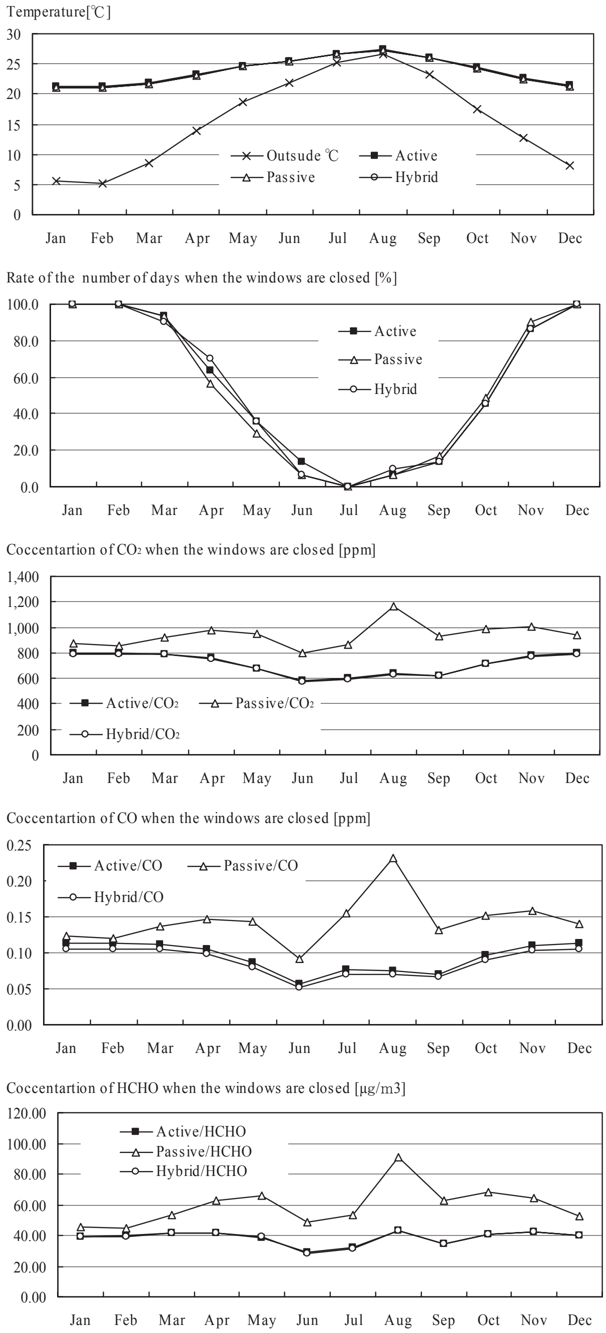


**Figure 6 Seasonal change of temperature and IAQ**

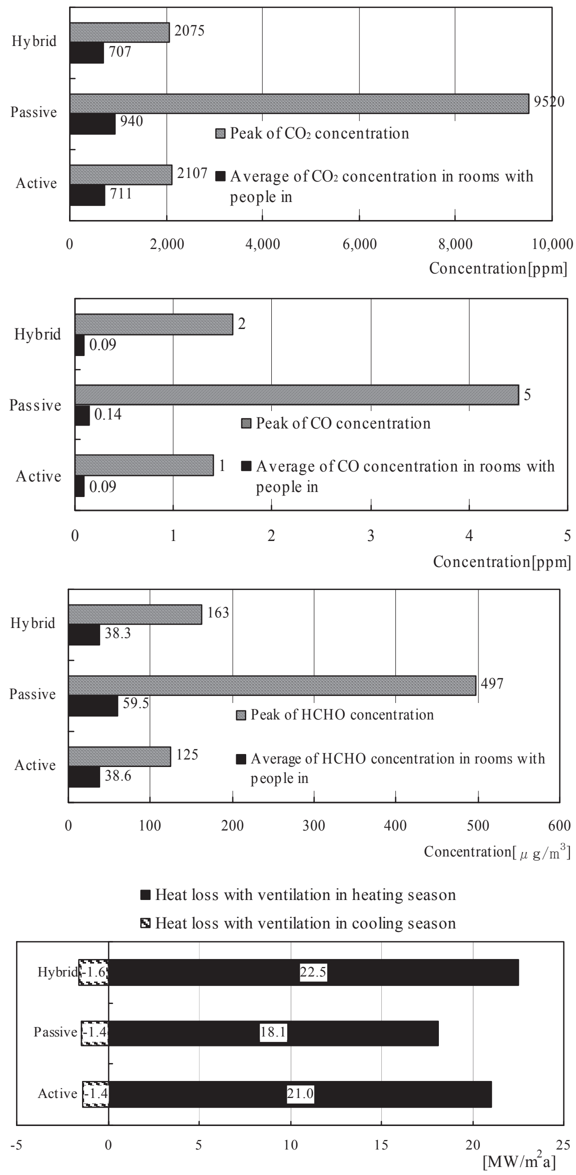


**Figure 7 Comparison concerning the IAQ and the heat losses with ventilation**

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