EVALUATION OF THE EFFECTS OF VENTILATION SYSTEMS ON TEMPERATURE, HUMIDITY, AIR QUALITY AND ENERGY CONSUMPTION IN MULTIPLE DWELLINGS

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ABSTRACT
Recently well-insulated and well-airtightened houses are increasing in Japan. Those houses have some problems of air quality because of formaldehyde from construction materials. Ventilation systems have possibility to solve these problems. The authors have developed a simulation program for designing building elements, equipment elements to keep balance among comfortable temperature and humidity, good air quality and energy conservation. The effects of some ventilation systems in multiple dwellings are revealed by the developed simulation program. The calculated results can be concluded as follows 1) In summer formaldehyde is at high concentration because of high emission rate. 24-hour mechanical ventilation or natural ventilation with large opening is necessary to keep the concentration low. 2) 24-hour mechanical ventilation systems require 30% more energy consumption than natural ventilation in summer. 3) The program is useful as a design tool by means of considering comprehensively various effects of factors such as ventilation.

INTRODUCTION
In Japan, well-insulated and well-airtightened houses designed for energy saving and the reduction of carbon dioxide emissions are increasing. These houses, however, have the problems of condensation, mould and indoor air pollution due to moisture generated in everyday life and formaldehyde and other substances released by construction materials. It is generally said that the higher the temperature or relative humidity, the higher the rate of formaldehyde emission from the construction materials[1)] , and temperature and humidity are closely related to air quality. Since ventilation for the prevention of air pollution and condensation may degrade the thermal environment and decrease energy saving efficiency, it is important to plan and evaluate building elements in a comprehensive manner. This paper introduces a simulation program that the authors have developed as a design tool for creating an energy-efficient, comfortable indoor environment that is comfortable in terms of temperature and humidity and has good air quality. The paper then reports on a case study of the relationships between ventilation systems and temperature, humidity, air quality and energy consumption in multiple dwellings.

DEVELOPMENT OF NUMERICAL SIMULATION
Outline
The authors have already developed a numerical simulation for calculating a temperature , humidity and energy consumption for multiple rooms[1)]. In the present study, the authors developed, by adding an air pollution evaluation model to the previously developed model, a simulation program that is capable of the following:
- Temperature and humidity evaluation using a model of simultaneous transfer of heat and moisture. (Appendix 1)
- Evaluation of interaction between rooms.
- Evaluation of movement of heat, moisture and pollutants during ventilation.

- Temperature/humidity and ventilation calculation and formaldehyde concentration coupled evaluation.
- Evaluation of heat load and mechanical ventilation energy consumption.
- Evaluation of conditions during the four seasons of the year (365 days).
- Heat/moisture generation and air conditioning schedules can be input.

Assumptions for Calculation of air pollution

- The rate of formaldehyde emission from wooden construction materials is calculated by referring to Inoue's equation (Appendix 2).
- Temperature and humidity of indoor air, not the construction materials, are used to calculate emission rates.
- Formaldehyde released by wooden materials is not readsorbed by the materials.
- Formaldehyde disperses uniformly in the rooms.

Verification of Calculation Accuracy

(1) Measurement in newly built multiple dwelling

On-site measurements of changes in temperature, humidity and formaldehyde concentration were made in a dwelling unit in a newly built multi-unit dwelling in Chofu City Tokyo Japan (Figure 1).[2)] The windows of the dwelling unit were closed and kept so for about 90 hours [from 16:30 on the 31st of July to 11:00 on the 4th of August], and changes in the indoor environment were

Table 1 Measuring methods (formaldehyde)

Name	Method
HPLC method	• Adsorption with DNPH cartridge (30 minutes) • Extraction of acetonitrile • Liquid chromatography
PAS method (See the note below.)	• Infrared opto-acoustic analysis using multi-gas monitor • Photo-acoustic Spectrometry • Measurement of changes over time in indoor concentration
Cap method	• Attaching a stainless steel cap at the measuring location • DNPH collection while circulating air • Liquid chromatography

Note: For the purpose of presentation, outputs are multiplied by 0.2 to make them correspond to the results obtained by the HPLC method (Figure 3).

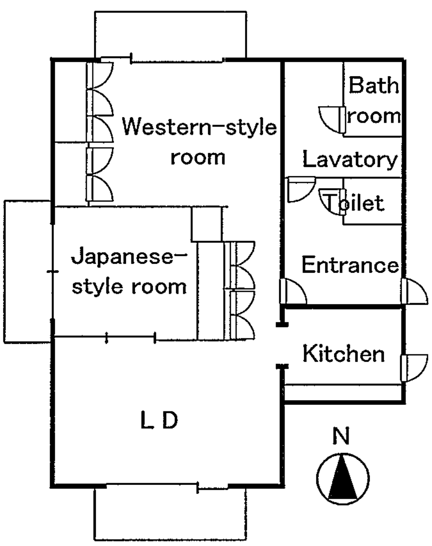


Figure 1 Dwelling unit

Table 2 Conditions for calculations for construction materials (formaldehyde)

Name of room	Materials & furniture	Desiccator content D[mg/l]	Indoor emission coefficient η [-][1)]	Attenuation coefficient ξ [-][2)]	Area [m²]
LD	Flooring(F2) Storage space(E1)	5.0 2.0	0.5 0.5	0.1 0.1	17.5 13.2
Japanese-style room	Closet (F2)	5.0	1.0	0.1	28.7
Western-style room	Storage space(E1)	2.0	0.5	0.1	97.6
Kitchen	Flooring(F2) Storage space(E1)	5.0 2.0	0.5 0.5	0.1 0.1	3.3 23.0
Entrance	Flooring(F2) Storage space(E1)	5.0 2.0	0.5 0.5	0.1 0.1	2.4 23.7
Toilet	Flooring(F2)	5.0	0.5	0.1	0.8
Lavatory	Flooring(F2)	5.0	0.5	0.1	1.9
Bathroom	None	—	—	—	—

Notes: 1) Resistance to emission from surface due to painting, etc., is taken into consideration. The figures in the table are assumed values.
2) Decreases in emission over time after manufacture. Adjustments were made to make the values correspond to the measured values.

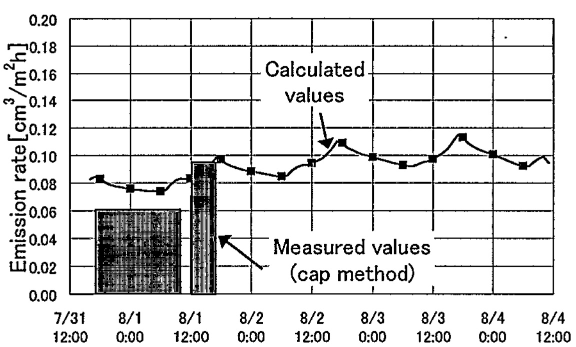


Figure 2 Rates of formaldehyde generation from floor (summer)

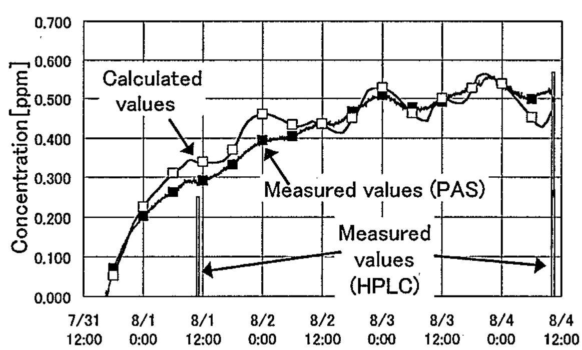


Figure 3 Formaldehyde concentrations (summer)

monitored by the three methods shown in Table 1.

(2) Numerical simulation

The results of the measurements of indoor temperatures and humidity and air quality are simulated numerically. Table 2 shows the conditions under which formaldehyde is emitted from the construction materials and furniture. The airtightness of the dwelling unit is 2.9 centimetres per square metre of floor (measured value). All interior doors including doors to storage spaces were kept open, so that the entire dwelling unit remained practically in a "single-room" condition. Out door temperature and humidity data were taken from data collected in the vicinity of the building . The solar radiation and nocturnal radiation data were taken from data collected in Otemachi, Tokyo. It is assumed that there is no wind outside the building, and only ventilation caused by temperature differences is considered in calculation and evaluation. Prior to the record period from the 31st of July, calculation was started on the 1st of July. There are no indoor sources of heat or moisture, no air conditioning, and no mechanical ventilation .

(3) Results

Formaldehyde emissions from the flooring surface measured by the cap method range from 0.060 to 0.095 cm^3/m^2h. Daytime emission rates are greater than night-time emission rates (Figure 2). In the simulation, when $\eta\ \xi=0.05$ (Table 2) is assumed, the measured values and the calculated values were of the same order. It is necessary to take into consideration that emission decreases over time after shipment from the factory (ξ) and that there is resistance to emission (η) due to surface finish, which cannot be measured by the desiccator method. When nonfloor materials and furniture are treated in the same manner as the floor , the calculated values and the measured values are of the same order (Figure 3). The calculated values capture formaldehyde concentration's tendency to gradually increase after the windows are closed.

CASE STUDIES

Conditions for Calculation

The four ventilation methods shown in Table 3 were studied for a dwelling unit (Figure 4) located on an intermediate floor of a multiple dwelling. Airtightness of the entire dwelling unit is 5.6 cm^2/m^2 when the register is open and 2.6 cm^2/m^2 when it is closed. It is assumed that wind is not blowing outside the dwelling, and natural ventilation caused by temperature differences and mechanical ventilation are considered. The doors between the rooms are closed. As for air pollutants, flooring (F2 type) with an indoor emission coefficient of 0.5 and an attenuation coefficient of 0.1 is assumed to calculate formaldehyde emission rates. It is also assumed that there is no heat capacity or moisture capacity of furniture, furnishings, etc., in the dwelling unit. The life pattern is defined by referring to the Architectural Institute of Japan's standard model[3)], assuming a four-member family . Heating and cooling temperatures are 22℃ and 26℃, and cooling humidity is 50% ,and intermittent air conditioning is assumed. Energy consumption is calculated by assuming a coefficient of performance of 2.5 of the heating and cooling system and adding the

Table 3 Ventilation methods considered

Ventilation method	Register	Ventilation facilities	Ventilation operation	Power consumption
No mechanical ventilation	Closed	None	None	0W
Local exhaust	Closed	Lavatory 30[m^3/h] Bathroom 35[m^3/h] Toilet 30[m^3/h]	Morning : 2 hours Evening : 2 hours	45W
24-hour local exhaust	Open	Lavatory 30[m^3/h] Bathroom 35[m^3/h] Toilet 30[m^3/h]	24 hours	45W
24-hour heat exchange & ventilation	None	Central total heat exchanger 90 (m^3/h) (thermal efficiency 70%)	24 hours	60W

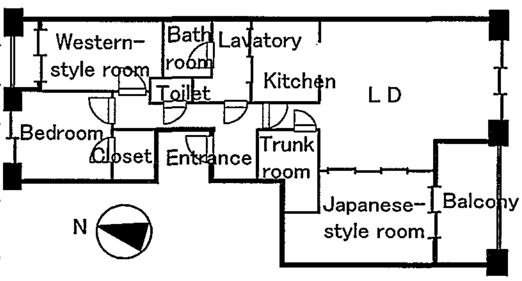


Figure 4 Dwelling unit selected for calculation

obtained value to the energy consumption of the ventilation fans. As for the meteorological conditions, Tokyo's standard meteorological data are used, and calculations for a period of one month each is carried out for winter (January) and summer (August).

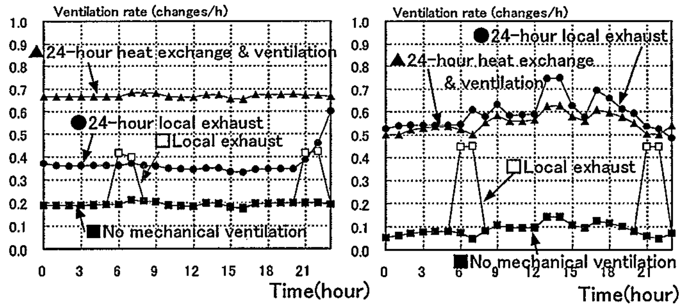
Results and Discussion

(1)In winter

The rate at which fresh outdoor air is taken into the living and dining room varies with the ventilation method. Under the "no mechanical ventilation" condition, the ventilation rate is 0.2 changes/h (Figure 5a). Temperature differences under the "no air-conditioning" condition are as small as about 1℃ (Figure 6a). The influence of cold draft, however, is not evaluated. Relative humidity is lower than 40%, regardless of the ventilation method; the higher the ventilation rate, the lower the humidity becomes (Figure 7a). The rate of formaldehyde emission rate does not vary with the ventilation method (Figure 8a). Formaldehyde concentration is the highest in the case of "no mechanical ventilation" where the ventilation rate is low(Figure 9a). Under the conditions assumed for the calculations, formaldehyde concentrations, even in the case of "no mechanical ventilation", are lower than the Ministry of Health and Welfare's guideline value (0.08 ppm). When only heating load is considered, the greatest amount of energy is consumed under the "24-hour heat exchange & ventilation" condition. When power consumed by the fans is taken into consideration, energy consumption increases to the level of "local exhaust" and becomes 14% higher than in the case of "no mechanical ventilation". Energy consumption is the greatest in the case of "24-hour local exhaust" because it requires power to drive the fans in addition to the heating loads (Figure 10a).

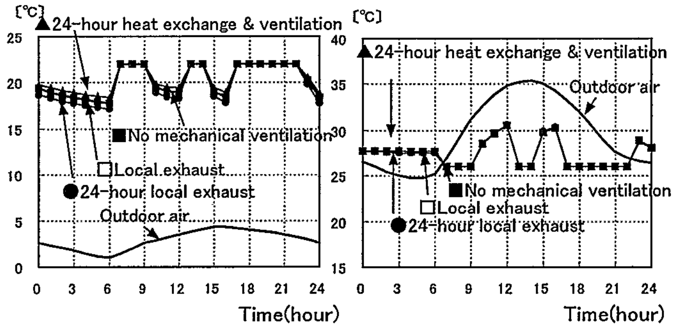
(2) In summer

Figure 5b shows changes in the rate at which fresh outdoor air is taken into the living and dining room on the hottest day of summer (8th of August). Since the dif-



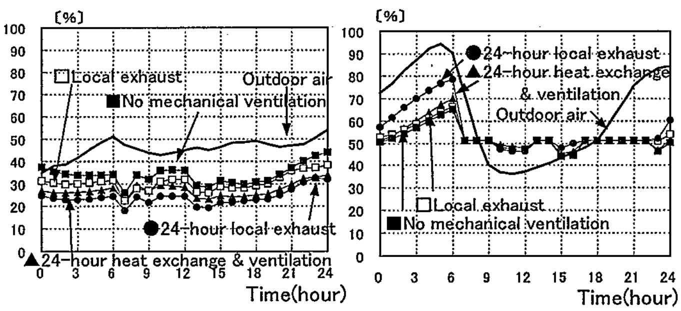
a) Winter(26th of January) b) Summer(8th of August)

Figure 5 Changes in the rate at which fresh outdoor air is supplied(LD)



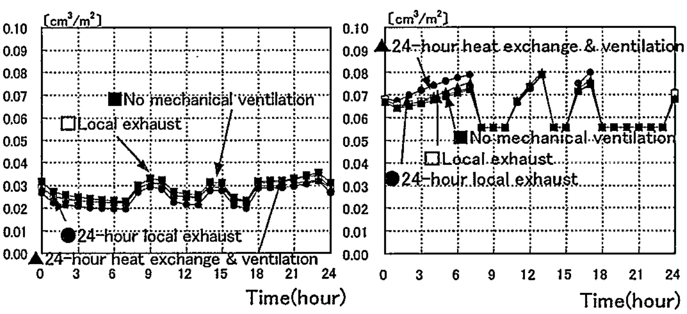
a) Winter(26th of January) b) Summer(8th of August)

Figure 6 Changes in temperature(LD)



a) Winter(26th of January) b) Summer(8th of August)

Figure 7 Changes in relative humidity(LD)



a) Winter(26th of January) b) Summer(8th of August)

Figure 8 Changes in formaldehyde emission rate(LD) ference between indoor and outdoor air temperatures in summer is smaller than in winter, the rate at which outdoor air is taken in under the "no mechanical ventilation" condition is as low as 0.1 changes/h. By performing mechanical ventilation, the ventilation rate of about 0.5 changes/h can be achieved. Because of small differences between indoor and outdoor air temperatures, there are no significant differences in temperature variations (Figure 6a). Relative humidity is higher than in winter (Figure 7b). Since temperature and humidity are higher than in winter, formaldehyde emissions in summer are two to four times as high as the winter emission levels (Figure 8b). In the case of "no mechanical ventilation", concentrations are as high as 0.5 ppm (Figure 9b). Concentrations under the conditions of "local exhaust" and 24-hour ventilation are 0.2 to 0.3 ppm and lower than 0.08 ppm, respectively. Because differences between indoor and outdoor air temperatures are not as great as in winter, there are no significant differences in sensible heat load (Figure 10b). Latent heat load increases as the ventilation rate increases, and it decreases in the case of 24-hour ventilation. Energy consumption including energy consumed by the fans in the case of 24-hour ventilation are about 30% greater than in the case of "no mechanical ventilation".

CONCLUSIONS

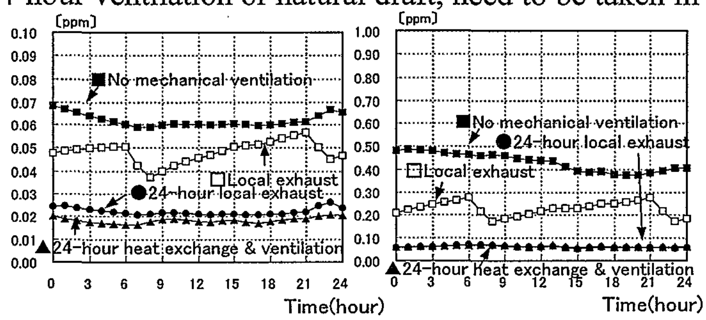
(1)A simulation program for comprehensive evaluation of temperature, humidity, air quality, and energy consumption in multi-unit dwellings has been developed. The calculated values well captured temperature, humidity, and formaldehyde concentration's in newly built multiple dwelling.

(2) Formaldehyde emissions in winter are roughly one half to one quarter of summer emission levels. Formaldehyde concentrations in winter are one order lower than in summer. From the viewpoint of indoor air quality, 24-hour ventilation is not necessarily needed in winter.

(3) Since formaldehyde emission levels are high and ventilation rates are low in summer, formaldehyde concentrations in summer are higher than in winter. Consequently, measures to lower formaldehyde concentrations, such as 24-hour ventilation or natural draft, need to be taken in summer , especially in first summer.

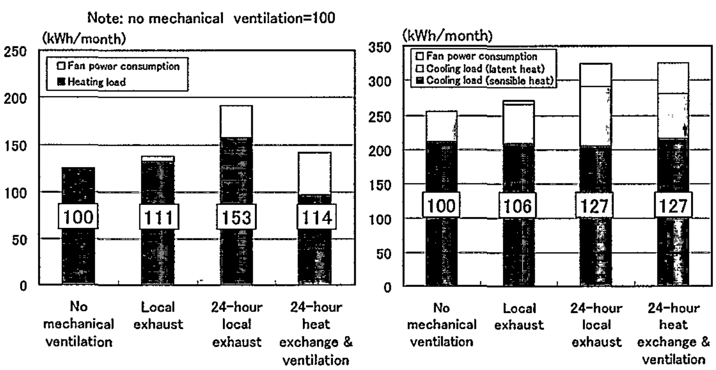
(4) If 24-hour ventilation is carried out in summer, energy consumption is about 30% higher than in the case of "no mechanical ventilation" because of increases in latent heat load and fan power consumption.

(5)The program is useful as a design tool by means of considering comprehensively various effects of factors such as ventilation.



a) Winter(26th of January) b) Summer(8th of August)

Figure 9 Changes in formaldehyde concentration(LD)



a) Winter(January) b) Summer(August)

Figure 10 Monthly energy consumption (entire dwelling unit)

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APPENDIX 1

■Simultaneous transfer of heat and moisture through wall

$$c\rho\frac{\partial\theta}{\partial t}=\lambda\frac{\partial^2\theta}{\partial x^2}+r\left(\lambda'\frac{\partial^2 X}{\partial x^2}\right)\cdots(1)\quad \kappa\frac{\partial X}{\partial t}=\lambda'\frac{\partial^2 X}{\partial x^2}+\nu\frac{\partial\theta}{\partial t}\cdots(2)$$

where

$$\kappa=\frac{\partial\varphi}{\partial X}\qquad \nu=-\frac{\partial\varphi}{\partial\theta}$$

[Symbols] c: specific heat, ρ : density, θ : temperature, t: time, λ : thermal conductivity, x: location, r: heat of adsorption, λ ': moisture conductivity, X: absolute humidity, φ : moisture content per unit volume

■Heat-moisture balance equation for wall surface

$$-\lambda\frac{\partial\theta_i}{\partial n}=\alpha_c(\theta_R-\theta_i)+\alpha_r\sum_j g_{i,j}(\theta_j-\theta_i)\cdots(3)$$

$$-\lambda'\frac{\partial X_i}{\partial n}=\alpha'(X_R-X_i)\cdots(4)$$

Surface concentration:

$$\frac{\partial H_i}{\partial t}=\alpha'(X_R-X_{SA,i})\cdots(5)$$

[Symbols] λ : thermal conductivity, θ : temperature, n: inward normal to surface, α_c: convective heat transfer coefficient, α_r: radiative heat transfer coefficient, $g_{i,j}$: radiation absorption coefficient, λ ': moisture conductivity
X: absolute humidity, α ': moisture transfer coefficient, H: surface moisture, t: time
[Suffixes] i: surface, j: surface, R: room, SA: saturated water vapor

■Heat-moisture balance equation for indoor air

$$c\rho U_R\frac{\partial\theta_R}{\partial t}=\sum_i\alpha_c S_i(\theta_i-\theta_R)+\sum_k(c\rho V_{k,R}\theta_k-c\rho V_{R,k}\theta_R)+c\rho V_{O,R}\theta_O-c\rho V_{R,O}\theta_R+q-L\cdots(6)$$

$$\rho U_R\frac{\partial X_R}{\partial t}=\sum_i\alpha' S_i(X_i-X_R)+\sum_k(\rho V_{k,R}X_k-\rho V_{R,k}X_R)+\rho V_{O,R}X_O-\rho V_{R,O}X_R+q_X-L_X\cdots(7)$$

[Symbols] c: specific heat, ρ : density, U: air volume, θ : temperature, t: time, α_c: convective heat transfer coefficient, S: area, V: ventilation volume, q: heat generation rate, L: heat extraction rate, X: absolute humidity, α ': moisture transfer coefficient, q_x : moisture generation rate, L_x : dehumidification
[Suffixes] i: surface, k: adjoining room, R: room, O : outdoor air

■Ventilation balance equation

$$0=\sum_{k,n}sgn(\Delta P_{R,k,n})\alpha A_n\sqrt{2g\rho\cdot|\Delta P_{R,k,n}|}\cdots(8)$$

$$V_{R,k}=-3600\sum_n\alpha A_n\sqrt{\frac{2g\Delta P_{R,k,n}}{\rho}}\cdots(9)\qquad \text{in case of }\ \Delta P_{R,k,n}>0$$

[Symbols] $\Delta P_{R,k,n}$: differential pressure at opening n between space R and space k, α A : effective area of opening, g : gravitational acceleration, ρ : density, V: ventilation volume
[Suffixes] R: room, k: adjoining room, n: opening

■Pollutant balance equation

$$U_R\frac{\partial}{\partial t}C_R=V_{O,R}C_O+\sum_k V_{k,R}C_k-(V_{R,O}+\sum_k V_{R,k})C_R+\sum_i m_i S_i\cdots(10)$$

$$m_i=\eta_i\xi_i(0.158D_i+0.017)\times1.09^{(\theta_R-23)}\times\frac{h_R+55}{100}\cdots(11)$$

[Symbols] U: air volume, t: time, C : formaldehyde concentration, V: ventilation volume, S: area
m : rate of formaldehyde emission from construction material, η : indoor emission coefficient, ξ : attenuation coefficient, D : desiccator content, θ : temperature, h : relative humidity
[Suffixes] R: room, O : outdoor air, k: adjoining room, i: surface

APPENDIX 2

Inoue's formaldehyde concentration equation is as follows[4]:

$$C=(0.158D+0.017)\times1.09^{(\theta-23)}\times\frac{h+55}{100}\times\frac{2}{1+V/S}\quad\cdots(12)$$

The equations on which Inoue based his equation are the following[5]:

$$U\frac{dC}{dt}=mS-a'SC-VC\quad\cdots(13)\qquad C_\infty=\frac{m}{a'+V/S}\quad\cdots(14)$$

If a'=1 is assumed as proposed by Inoue, emission m from one surface of a construction material can be calculated from Eqs. (12) and (14):

$$m=2(0.158D+0.017)\times1.09^{(\theta-23)}\times\frac{h+55}{100}\quad\cdots(15)$$

where

C: formaldehyde concentration, C_∞: steady state formaldehyde concentration, V: ventilation air volume, θ : temperature, h: relative humidity, S: area, D: desiccator content, a': adsorption coefficient of formaldehyde, U: room air volume