

Development of an Integrated Energy Simulation Tool for Buildings and MEP Systems, the BEST (Part 13)

A Simulation Method of Thermal Load and Space Environment

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1. Introduction

This report concretely describes a simulation method of building thermal behavior. This calculation method has 2 features: the variable calculation time interval and the solving method switching depending on whether the time zone needs an integrated solution with an HVAC system or not. First, the solving methods for the thermal equilibrium equation of a room are described. Next, calculation methods for the thermal load of each component (e.g., wall and window) are described.

2. The thermal equilibrium equation of space and the solving methods

A thermal equilibrium equation of the space i is set up under the conditions where the space air temperature is unknown and the interactions between spaces have to be considered. An equation regarding the sensible heat of the space i can be summarized as follows:

$$C_i(d\theta_i/dt)_n = K_{i,i,n} \cdot \theta_{i,n} + \sum_j K_{i,j,n} \cdot \theta_{j,n} + F_{i,n} \dots (1)$$

where

C_i : thermal capacity of the space i [J/K];

θ_i : air temperature of the space i [°C];

$d\theta_i/dt$: derivative value of air temperature of the space i [K/sec];

n : current time step;

K_{ij} : coefficient for the space j in the thermal equilibrium equation of the space i ; and

F_i : constant term [W].

If an integrated solution with an HVAC system is not required, the left side of equation (1) can be rewritten as a backward difference and the $\theta_{i,n}$ (the air temperature of the space i) and $\theta_{j,n}$ (the air temperature of the adjacent space j) can be dealt with as an unknown. Accordingly, the thermal equilibrium equations for the multiple spaces can be solved as simultaneous equations (hereinafter called the backward

method). If an integrated solution with an HVAC system is required, the 4th order Runge-Kutta method is applied because this method is appropriate, especially for HVAC systems that are associated with many nonlinear discontinuous phenomena. This method calculates the state values at the next time step under the assumption that the space air temperature and the state values at the current time step are known (hereinafter called the forward method). The forward method needs a shorter calculation time interval to some degree. Consequently, the space air temperature responses for weather, internal heat generation and heat supply due to HVAC system operations can be simulated in detail. For seasons when only ventilation is required, the backward method may be applied if appropriate, without using a short calculation time interval. This approach is under examination.

Space air humidity can be dealt with as an unknown value just like space air temperature. As well as sensible heat, the thermal equilibrium equation for latent heat of multiple spaces can be solved by switching the 2 solving methods (the forward and backward method) from one to the other depending on the situation.

The problem is how to deal with the boundaries of the forward and backward methods. Figure 1 is an example pattern of the solving method switch. If the backward method is applied until 07:55, the calculated value by the backward method is used as the space air temperature at 07:55. If the backward method is switched to the forward method at 08:00, the space air temperature at 08:00 is assumed to be equal to the temperature at 07:55 for convenience because the temperature at 08:00 has to be a known value. In order to reduce the error due to this assumption, the calculation time interval just before the switch point has to be shortened. If the forward method is applied until 22:00, the calculated value is the space air temperature at the next time step (21:00), but it is not used. The solution of the backward method at 21:00 is to be used

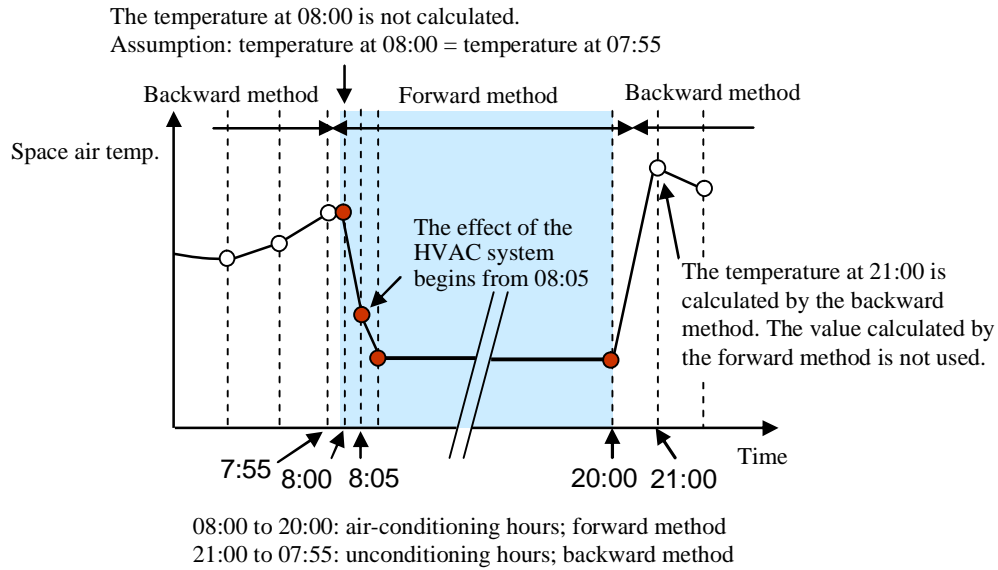


Figure 1: Example pattern of solving method switch

as the space air temperature at 21:00. A method to select the most appropriate calculation time interval in the forward method requires further study.

3. Calculation method for each thermal load component

In this Section, calculation methods for thermal behavior at walls and windows are described. Then, the calculation method for thermal behavior at each of the other components and the calculation method for the thermal environmental index (PMV) are described.

In the calculation method for conductive heat through walls, Matsuo's Common Ratio Method, which can accept a variable calculation time interval, is applied. In this method, surface temperatures of walls are not dealt with as unknown values and the convective and radiation portions are approximately separated by using the response of the space thermal load W to the space heat gain. Vertical air-temperature distribution, including airflow along wall surfaces, is planned to be incorporated into this calculation method. Considering this plan, this method is designed so that each wall surface temperature inside the space can be calculated after solving the heat balance equations. Accordingly, the convective heat that transfers sequentially from each wall surface, i.e., the wall thermal load, is calculated under the assumption that penetrated solar radiation and the radiation component of internal heat generation is absorbed by a prescribed surface. Equations for calculating a wall thermal load are summarized in Table 1.

As shown by equation (4-2), the effect of radiation heat absorbed by the outside surface of the inner wall can also be considered. The equation for a wall thermal load (excluding windows) can be summarized as equation (5). Accordingly, thermal load from the wall surface can be calculated by using wall transfer functions T and A regarding the response of thermal load to outside equivalent air temperature and inside equivalent air temperature. For the conversion of the heat gain response into thermal load response, Matsuo's Common Ratio Method is also applied as shown in Table 2. In order to approximate the wall transfer functions regarding the response of thermal load, five roots (fixed values) are used here. It is planned that this approximation method will be improved so that the wall transfer functions will be approximated by deriving the most appropriate 2 roots for each wall. Table 3 shows the calculation procedures based on Matsuo's Common Ratio Method where the calculation time interval is variable. Under the assumption that scalene triangle waves excite as shown in Figure 2, an equation is derived based on Matsuo's Common Ratio Method, for which equations for isosceles triangle wave excitation are used. As for the thermal characteristics of furniture, the study results on thermal responses of office furniture by Ishino, Kohri, et al. are used. The effects of furniture on a space thermal load are considered.

As shown in equation (1) in Table 4, the window heat gain is expressed as the total of the conductive heat gain, the heat

Table 1: Calculation method for wall thermal load

Wall thermal load

An equation of the wall thermal load $Q(s)$ can be written as follows by using the heat gain $HG(s)$ and the space transfer function $W(s)$ regarding the space thermal load response to the space heat gain.

$$Q(s) = HG(s) \cdot W(s) \quad \dots(1)$$

$HG(s)$ can be written as follows by using the equivalent inside air temperature $t_{re}(s)$, the equivalent outside air temperature $t_{oe}(s)$ and the radiation heat $RI(s)$ absorbed by the inside surface;

$$HG(s) = t_{TO}(s) \cdot t_{oe}(s) - A_{AO}(s) \cdot t_{re}(s) + RI(s) \quad \dots(2)$$

Where

$$t_{re}(s) = t_r(s) + RI(s)/h_t \quad \dots(3)$$

in the case of an outside wall,

$$t_{oe}(s) = t_o(s) + (I(s) - RN(s))/h_{to} \quad \dots(4-1)$$

or in the case of an internal wall
(the air temperature of the adjacent space is unknown),

$$t_{oe}(s) = t_{ro}(s) + RO(s)/h_{to} \quad \dots(4-2)$$

With the equations (1) to (3), $Q(s)$ can be summarized as follow;

$$Q(s) = t_T(s) \cdot t_{oe}(s) - A_A(s) \cdot t_{re}(s) + W(s)RI(s) \quad \dots(5)$$

Where

$$t_T(s) = t_{TO}(s)W(s) \quad \dots(6-1)$$

$$A_A(s) = A_{AO}(s)W(s) \quad \dots(6-2)$$

Inside surface temperature

The inside surface temperature t_s [°C] can be calculated by using the convective heat q [W/m²] from the inside surface and the inside convective heat transfer coefficient h_c [W/m²K] based on the following equation.

$$t_s = q/h_c \quad \dots(7)$$

Symbols

- h_t : inside total heat transfer coefficient;
 - h_{to} : outside total heat transfer coefficient;
 - t_o : outside air temperature;
 - t_r : space air temperature;
 - t_{ro} : adjacent space air temperature;
 - I: solar radiation absorbed by the outside wall surface;
 - R_N : nocturnal radiation absorbed by the outside wall surface;
 - RO: radiation heat (e.g., solar radiation and internal heat generation) absorbed by the surface of an internal wall in the adjacent space;
 - $T_{TO}(s)$: wall transfer functions regarding the heat gain response to the outside equivalent air temperature;
 - $A_{AO}(s)$: wall transfer functions regarding the heat gain response to the inside equivalent air temperature;
 - $t_T(s)$: wall transfer functions regarding the thermal load response to outside equivalent air temperature; and
 - $A_A(s)$: wall transfer functions regarding the thermal load response to the inside equivalent air temperature
-

radiation component of internal heat generation) and the convective component and long-wave radiation portion of the

Table 2: Conversion method from wall heat gain to wall thermal load

The space transfer function $W(s)$ in Table 1 can be calculated by using the wall transfer function $A_{AOi}(s)$ regarding the response of the heat gain to the inside equivalent temperature of each wall based on the following equation;

$$W(s) = h_c \cdot A_{wt} / (h_c \cdot A_{wt} + h_r \cdot A_{wi} (A_{AOi}(s)/h_t)) \quad \dots(1)$$

Where

$$A_{wt} = \sum_i A_{wi} \quad \dots(2)$$

The wall transfer functions regarding the thermal load response to the outside equivalent air temperature $t_T(s)$, to the inside equivalent air temperature $t_A(s)$ and to the radiation heat absorbed by the inside surface $R(s)$ can be approximated by using the root of k (fixed value). For example, $t_T(s)$ can be approximated as follows.

$$t_T(s) = W(s) \cdot t_{TO}(s) = A_0 + \sum_{k=1}^{k_0} A_k \cdot s / (s + k) \quad \dots(3)$$

A_k can be calculated by solving the simultaneous equations under the condition where the equation (3) is appropriate in the limited range of

$$s = k \quad (k = 1 \text{ to } k_0);$$

Where

$$k = \{0.014, 0.058, 0.24, 1.0, 4.2\} [\times 10^{-3} \text{ 1/sec}] \dots(4)$$

Symbols

- h_c : inside convective heat transfer coefficient;
 - h_r : inside radiation heat transfer coefficient;
 - h_t : inside total heat transfer coefficient;
 - A_{wt} : total of the inside surface areas;
 - A_{wi} : inside surface area of the wall i ;
 - k_0 : number of the root;
 - k : root; and
 - A_0 and A_k : coefficients of the step response.
- For other symbols, see Table 1.
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solar heat gain, excluding the solar radiation through windows. The window thermal load can be calculated by using the window heat gain and equation (1) in Table 1 based on Matsuo's Common Ratio Method just like the wall thermal load calculation. In this way, equation (7) in Table 1 can be used to calculate window surface temperature by calculating the wall thermal load. However, the solar radiation penetrating the windows is assumed to be absorbed by the floor and furniture surface. As shown in Table 4, each of the solar heat gain components can be calculated by using the solar heat gain coefficients, window transmittances and long-wave radiation factors. Applicable windows at the current stage are conventional windows and airflow windows (hereinafter called AFW). As for the thermal performance of windows, the conventional window performance data in the database will be extracted and used. If the window performance regarding solar radiation is

Table 3: Calculation method with a variable calculation time interval based on Matsuo's Common Ratio Method

In order to apply Matsuo's Common Ratio Method, this Method has to be modified to accept a variable calculation time interval. The response to scalene triangle wave excitation (see Figure 2) during the time series of n ($n = 0, 1, \dots$) can be expressed by the following equations;

$$x_0 = A_0 + \sum_{k=1}^{k_0} X_{k,0} \quad \dots(1-1)$$

$$x_1 = \sum_{k=1}^{k_0} Z_{k,1} = \sum_{k=1}^{k_0} (R_{k,1} \cdot X_{k,0} - X_{k,1}) \quad \dots(1-2)$$

$$x_n \quad (n \geq 2) = \sum_{k=1}^{k_0} Z_{k,n} = \sum_{k=1}^{k_0} R_{k,n} \cdot Z_{k,n-1} \quad \dots(1-3)$$

$$\text{ただし、} R_{k,n} = e^{-k \cdot T_n} \quad \dots(2)$$

$$X_{k,n} = \{A_k / (k \cdot T_n)\} (1 - R_{k,n}) \quad \dots(3)$$

If the time series n regarding temperature fluctuation is given, the thermal response q_n at the time step n can be expressed by the following equation;

$$q_n = q_{0,n} + \sum_{k=1}^{k_0} Z_{k,n} \quad \dots(4)$$

$$q_{0,n} = A_0 + \sum_{k=1}^{k_0} X_{k,n} \quad \dots(5)$$

$$Z_{k,n} = R_{k,n} \cdot Z_{k,n-1} + (R_{k,n} \cdot X_{k,n-1} - X_{k,n}) \quad \dots(6)$$

Where

$$Z_{k,1} = (R_{k,1} \cdot X_{k,0} - X_{k,1}) \quad \dots(7)$$

Symbols

T_n : calculation time interval [sec] (the difference between the current and the previous calculation time point); and

$0,n$: response value to the scalene triangle wave excitation at the time 0

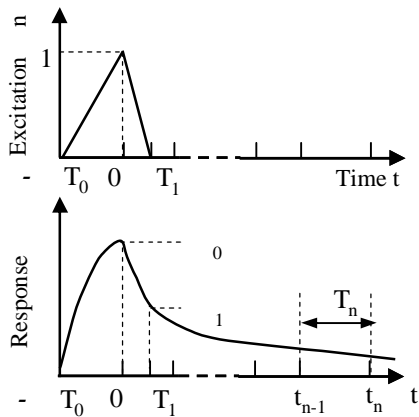


Figure 2: Response to scalene triangle pulse excitation

Table 4: Calculation methods for window thermal load and solar heat gain

Window thermal load

After the heat gain HG [W/m²] is calculated, the window thermal load can be calculated by using the equation (1) in Table 1. The equation (1) in Table 1 can be rewritten by using the outside air temperature θ_o [°C], the space air temperature θ_r [°C], the nocturnal radiation absorbed by the outside wall surface R_N [W/m²], the radiation heat absorbed by the inside wall surface RI [W/m²] and the convective and the long-wave radiation portion of the solar heat gain $HG_{SR,C+LR}$ are [W/m²] as follows.

$$HG = U (\theta_o - RN/h_{to} - \theta_r) + RI (1 - U/h_i) + HG_{SR,C+LR} \quad \dots(1)$$

Symbols

U : window U-factor [W/m²K];

h_i : inside total heat transfer coefficient; and

h_o : outside total heat transfer coefficient

Solar heat gain

The short-wave radiation portion $H_{GSR,SR}$, the long-wave radiation portion $HG_{SR,LR}$ and the convective portion $HG_{SR,C}$ of the solar heat gain can be calculated by the following equations.

$$HG_{SR,SR} = I_D \cdot D + I_S \cdot SKY + I_G \cdot GR \quad \dots(2)$$

$$HG_{SR,LR} = k_{LR} (HG_{SR} - HG_{SR,SR}) \quad \dots(3)$$

$$HG_{SR} = I_D \cdot D + I_S \cdot SKY + I_G \cdot GR \quad \dots(4)$$

$$HG_C = HG_{SR} - HG_{SR,SR} - HG_{SR,LR} \quad \dots(5)$$

Symbols

I_D : direct solar radiation incident on a window [W/m²];

I_S : sky solar radiation incident on a window [W/m²];

I_G : reflected solar radiation from the ground incident on a window [W/m²];

D : window transmittance to the direct solar radiation [-];

SKY : window transmittance to the sky solar radiation [-];

GR : window transmittance to the reflected solar radiation from the ground [-];

k_{LR} : coefficient for the long-wave radiation component;

D : solar heat gain coefficient for the direct solar radiation [-];

SKY : solar heat gain coefficient for the sky solar radiation [-];

and

GR : solar heat gain coefficient for the reflected solar radiation from the ground

required, however, the difference in the incidence conditions of solar radiation has to be corrected. If the window U-factors are required, the difference in the thermal resistance of the gas space has to be corrected as well. As for the AFW performance, another correction is required based on the airflow rate of the window other than the corrections described above. The correction methods are given in Table 5. The equations (6), (7) and (9) in Table 5 are

Table 5: Calculation method for thermal performance of a window

Solar shading performance

The D_D and the D_D (see Table 4) of a conventional window can be calculated by the following equations. In other words, the D_D and the D_D extracted from the database have to be corrected because these values were obtained under the standard solar incidence conditions. As for the D_{SKY} , D_{GR} , D_{SKY} and D_{GR} extracted values from the database are used without correction.

$$D_D = f(i) \dots (1) \quad f(i) = \sum_{n=1}^5 A_n \cdot \cos^n i \dots (2)$$

$$D_D = g(i) \dots (3) \quad g(i) = \sum_{n=1}^5 B_n \cdot \cos^n i \dots (4)$$

The D_D of an AFW can be calculated by adding the correction value r to the value of the AFW without ventilating, i.e. to the value of a conventional window D_D with the same glass blind specification. The window transmittance and long-wave radiation component coefficient are the same as those of the AFW without airflow.

$$D_D = D_D + r \dots (5)$$

Where $r = (D_D - D_D) \cdot r \dots (6)$

$$r = C_0 + C_1 \cdot e^{-1 \cdot V} + C_2 \cdot e^{-2 \cdot V} \dots (7)$$

Window U-factor

As for a conventional window, the U-factor and the long-wave radiation component coefficient can be extracted from the database. If the gap thickness between glasses or the type of filler gas is different, the U-factor has to be corrected. As for an AFW, the value of an AFW without ventilating has to be corrected.

$$U = U + U \dots (8)$$

Where

$$U = D_0 + D_1 \cdot e^{-1 \cdot V} + D_2 \cdot e^{-2 \cdot V} \dots (9)$$

Symbols

- f: normalized solar heat gain coefficient [-];
- g: normalized window transmittance [-];
- i: solar radiation incidence angle;
- A_n and B_n : approximation coefficients;
- D_D and D_D : solar heat gain coefficient and window transmittance of a conventional window with the same specifications of glass and blind as those of AFW[-];
- r : correction value of the solar heat gain coefficient based on the difference in the airflow rate [-];
- r : correction coefficient based on the difference in the airflow rate [-];
- V: airflow rate [liter/sec];
- $C_0, C_1, C_2, 1$ and 2 : approximation coefficients;
- U' : window U-factor of a conventional window with the same same specifications of glass and blind as those of AFW [W/m²K];
- U : correction value of the window U-factor based on the difference in the airflow rate [W/m²K]; and
- $D_0, D_1, D_2, 1$ and 2 : approximation coefficients

equations newly proposed in this report. The assumed slot angle of window shades is 45 degrees only at the current stage. However, a new calculation

method that can accept slot angle variation is planned to be developed. As for external window shades, the effects of horizontal and vertical louvers can be also calculated. The effects of adjacent buildings are also planned to be included.

Draft air can be calculated by the following two methods: a method using a given air exchange rate and a method calculating the envelope leakage rate by using the outer surface area of the building. The air exchange rate between each zone can be calculated by entering the boundary lengths between each zone and the airflow rate per boundary length.

As for a calculation of heat generation from human bodies, a simplified two-node model is applied to determine the heat transfer ratios of the 3 components: convective, radiation and latent. In this method, the heat transfer amount of the each component is calculated by entering the metabolic rate, clothing, airflow velocity, operative temperature and humidity ratio. The last two state values are provided by the calculations at the previous-time step. Heat generation due to lighting and equipment operations can be calculated by entering the maximum wattage, maximum sensible heating value and maximum latent heating value. The input values, such as the ratio of people in the space, ratio of operated lighting fixtures and ratio of operated equipment, are any values at a certain time. The state values of each time step can be calculated using a linear interpolation method based on these input values.

After the thermal equilibrium for space and systems are solved, a thermal environmental index (PMV) can be calculated. Rather than MRT, the AST of each zone is used in this calculation.

4. Future challenges

An approach to leverage the advantages of the variable calculation time interval has to be established and promoted first. Then, studies on the setting method for the most appropriate calculation time interval in the integrated calculation method for systems and studies on the usage of different calculation time intervals between the building and the systems have to be conducted. Incorporation of block models into the calculation method and the evaluation of vertical air-temperature distribution are also included in future challenges that must be overcome.

5. Conclusion

This report describes the calculation methods for thermal loads and inside environments. In the thermal load calculation method, the calculation time interval is variable and the 2 solving methods (the forward and backward methods) can be switched from one to the other.

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