Features and Capabilities of an Integrated Building Energy Simulation Tool, BEST, Developed in Japan

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ABSTRACT

The present paper proposes a whole-building energy simulation software application that has been continuously developed and upgraded in Japan. This tool can perform simultaneous coupled simulations that consider the interactions between the building envelope, building structure, internal heat generation, HVAC systems, electrical systems, and plumbing systems. The present paper describes the concept and features of the latest version of the tool. In particular, simulation methods and simulation results that reveal the capabilities of the tool are presented.

INTRODUCTION

A dynamic thermal load calculation program (Y. Matsuo et al. 1980) and a system simulation program (JABMEE 1986) were developed around 40 years ago as annual HVAC energy simulation tools in Japan. They are not for integrated simulations and it is hard to improve their solution algorism. The proposed tool was developed as a new and more effective simulation tool through a collaboration between industry, government, and academia, consisting of general contractors, designers, manufacturers, universities, and government agencies, such as the Ministry of Land, Infrastructure, Transport and Tourism, in 2005. The initial version of this tool was released in March of 2008 and has been updated continuously since its release. The latest version was released in February of 2016.

The Building Energy Simulation Tool (hereafter "the tool") attempts to satisfy the needs of the building industry, as a design and operation tool, government agencies, as a calculation tool for the application of building confirmation, and academia, as a research and education tool for studying building energy consumption and indoor environments.

DEVELOPMENT OF THE TOOL

The tool is being continuously developed in several areas, to provide a number of distinctive features.

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1. Whole-building energy consumption can be obtained through simulations integrating building thermal behavior and control of HVAC systems, as well as electrical and plumbing systems.
2. The tool can be used for various types of evaluation, including energy simulations and conventional thermal load simulations, such as simulation of design peak load and annual load. The spatial variation of thermal comfort can also be evaluated.
3. Two types of user interfaces are currently provided with the tool, and the user can select the appropriate interface for his/her specific application. The expert interface can be used for research or detailed examinations. The designer interface can be used to design energy-saving buildings and systems as well as confirm energy savings.
4. The user interfaces are easy to use. A default value is given for each input item, and graphical interfaces can be used with the designer interface.
5. The tool is being continuously refined and extended. The program codes are written in Java, which is flexible and expandable and enables object-oriented programming. Support services for users are also provided.

FEATURES OF THE SIMULATION ENGINE AND DATABASES

The simulation engine of the tool consists of components for building simulation and for system simulation. Thermal load simulations require only the building simulation component, and integrated energy simulations require both the building and system simulation components.

Building Simulation Component

The building simulation component of the engine has the following features.

1. Two techniques for solving heat balance equations can be used depending on the simulation state. For integrated energy simulations, an explicit technique can be used to solve the heat balance between zones and systems, and an implicit technique can be used to solve the heat balance between zones while suspending system operation. An implicit technique is always used for thermal load simulation in order to obtain the required cooling/heating rate or unconditioned space conditions.
2. The simulation time interval can be changed according to the cooling/heating schedule. Short time intervals are suitable for solutions obtained using an explicit technique as well as rapidly changing conditions in the space of interest. A time interval of 60 minutes, for example, is sufficient for use in an implicit technique for slowly changing conditions.
3. Thermal interactions between zones can be simulated, and there is no upper limit on the number of zones.
4. The radiant heat transfer can be solved approximately. In sensible heat balance equations for zones, the unknown variables are zone air temperatures or sensible supply heat rates and not surface temperatures. The delay of heat transfer due to radiation absorbed by surfaces is considered using transfer functions of the response of convective heat to the convective and radiant heat gain. This method does not require 3D information and is not limited in terms of space shape.
5. In the case of design peak load calculation, daily periodic unsteady state thermal load simulations can be performed under various weather conditions on design weather days. For intermittent heating and cooling, special conditions of early starts for operation can be assumed in order to avoid overdesign.
6. Space thermal comfort sensation indices, such as operative temperature and PMV, can be obtained.
7. The effects of window systems, such as airflow windows (AFWs) and naturally ventilated double-skin facades (DSFs), can be evaluated. The theoretical formulae for thermal performance, including the U-value and solar heat gain coefficient, have been derived and enable performance prediction based on the vertical distribution of air temperature in the ventilated cavity.
8. Indoor natural ventilation is simply simulated. Airflow balance is not solved and the height of the neutral zone is assumed. Various conditions for control of natural ventilation can be set for simulations.

9. The energy saving effects of lighting control with automatically adjusting blinds can be obtained using a simplified estimation of the horizontal illuminance distribution in the cross-section of the space.

System Simulation Component

The system simulation component of the engine has the following features.

1. Heat balance equations are solved using an explicit technique, preferably at five minute intervals.
2. The behavior of each piece of equipment is expressed as a Java class according to the rules associated with data transmission. The class is called a module. Modules are interconnected in order to configure the entire system. Such a modular structure enables the use of a wide variety of modeling techniques and also has the advantages of ease of both maintenance and extension of the program.
3. By developing various modules, users can simulate entire complex systems, including not only HVAC equipment but also electrical and plumbing equipment.
4. Templates are provided for easy configuration of entire HVAC systems. Templates are sets of pre-configured modules, such as AHUs and chillers in combination with a cooling tower.
5. Control elements are prepared as modules independent from other parts of the engine. Therefore, several types of control can be selected, and modules for new control algorithms can be easily added.
6. Modules are prepared for various HVAC systems, including both decentralized and central systems, as well as systems for effective use of energy, such as thermal storage tank systems, co-generation systems, and photovoltaic panels. The tool can be used for the planning of zero-energy buildings (ZEBs).

Databases

The tool can be applied to a wide variety of weather databases. The 2006 weather dataset for Tokyo with intervals of one minute, which was developed for the tool, and the Expanded AMeDAS Design Weather Datasets for 840 locations in Japan are included in the tool. Typical year weather datasets, such as EPW and Expanded AMeDAS, as well as design weather datasets, such as WEADAC (which contains data for 3,700 cities throughout the world), can also be used after being obtained by the user.

Fenestration databases containing the thermal and optical properties of windows were developed specifically for the tool. These databases include a database for 4,200 typical windows and a database for 1,700 window systems. A database of the thermal properties of wall materials for 150 Japanese materials and 160 foreign materials is also incorporated into the tool.

HVAC equipment performance databases were prepared for central systems and decentralized systems and continue to be extended.

Validation

The tool was tested using a method of test for the evaluation of building energy analysis computer programs. Its test procedures are now standardized as ANSI/ASHRAE Standard 140-2011. The validity of the tool was confirmed by comparing the values of peak load, annual load, and electricity consumption obtained from the tool with the simulation results of several tools that are commonly used in various countries. Furthermore, the measured and simulated values obtained using other domestic programs were compared, and the results of a sensitivity analysis of the simulation results were made public (M. Kuboki et al. 2011).

SIMULATION METHODS

The tool incorporates original methods for obtaining the heat balance solution, simulating heat transfer around walls, and the thermal performance simulation of window systems.

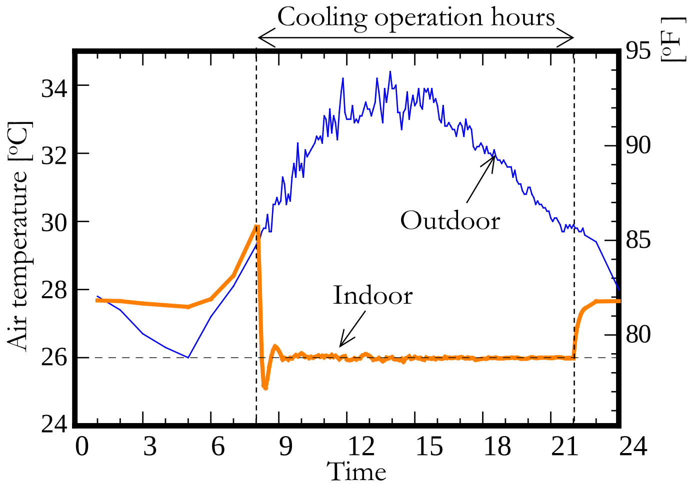
Heat Balance Solution between Zones and Systems

The key features of the simulation method are the ability to switch solution techniques and the ability to change simulation time intervals. The tool incorporates explicit and implicit solution techniques.

In the explicit technique, the current state is known. The state during the next time step is unknown and can be obtained by the Runge-Kutta Method, which is a simple explicit solution technique. Each of the heat balance equations can be solved individually with shorter time intervals. This technique is applicable to the heat balance solution for systems having tendencies of non-linear behavior as well as discontinuous changes. In order to solve for the heat balance equation, control elements must be assumed. In an implicit solution, the current state is unknown and the heat balance is expressed as simultaneous equations. Zone heat balance equations can be linearized, and so the heat balance between zones that are free from interaction with complex systems can be solved using matrices. Short time intervals are not necessary for this solution.

In the tool, the explicit technique must be used to solve the heat balance between zones and system components. However, the solution technique can be changed to the implicit technique to solve the multi-zone heat balance while system operations are suspended. For thermal load simulations, the implicit technique is usually used.

Figure 1 shows zone air temperature changes as the results of switching solution techniques in the case of intermittent cooling operation, which is popular in Japan. The heat balance was solved using the explicit technique during cooling operation hours and using the implicit technique outside of operation hours.



Cooling operation hours (8:05-22:00)
Time interval: 5 minutes
Solution technique: Explicit
Outside cooling operation hours (22:05-8:00)
Time interval:
Basically 60 minutes
5-30 minutes for an hour after switching solution techniques
Solution technique: Implicit

Figure 1 An example of simulation results obtained by changing solution techniques

Heat Conduction Simulation Allowing Changes of Time Intervals

It is necessary for the tool to prepare a wall conduction simulation method that allows time interval changes. Therefore, Matsuo's method (Matsuo 1970) was extended to be applicable to any time interval schedule. The equations of the extended Matsuo's method were derived using the equations of the response factors of heat flux from the wall surface to a unit scalene triangular pulse of outside or inside temperature. The heat flux q_n due to the fluctuation of temperature θ_n is obtained as follows:

$$q_n = \varphi_{0,n} \cdot \theta_n + \sum_{k=1}^{k0} Z_{k,n} \qquad \ldots (1)$$

$$\varphi_{0,n} = A_0 + \sum_{k=1}^{k0} X_{k,n} \qquad \ldots (2)$$

$$Z_{k,n} = R_{k,n} \cdot Z_{k,n-1} + (R_{k,n} \cdot X_{k,n-1} - X_{k,n})\theta_{n-1} \qquad \dots (3)$$

$$X_{k,n} = \{A_k / (\alpha_k \cdot \Delta T_n)\}(1 - R_{k,n}) \qquad \dots (4)$$

$$R_{k,n} = e^{-\alpha_k \cdot \Delta T_n} \qquad \dots (5)$$

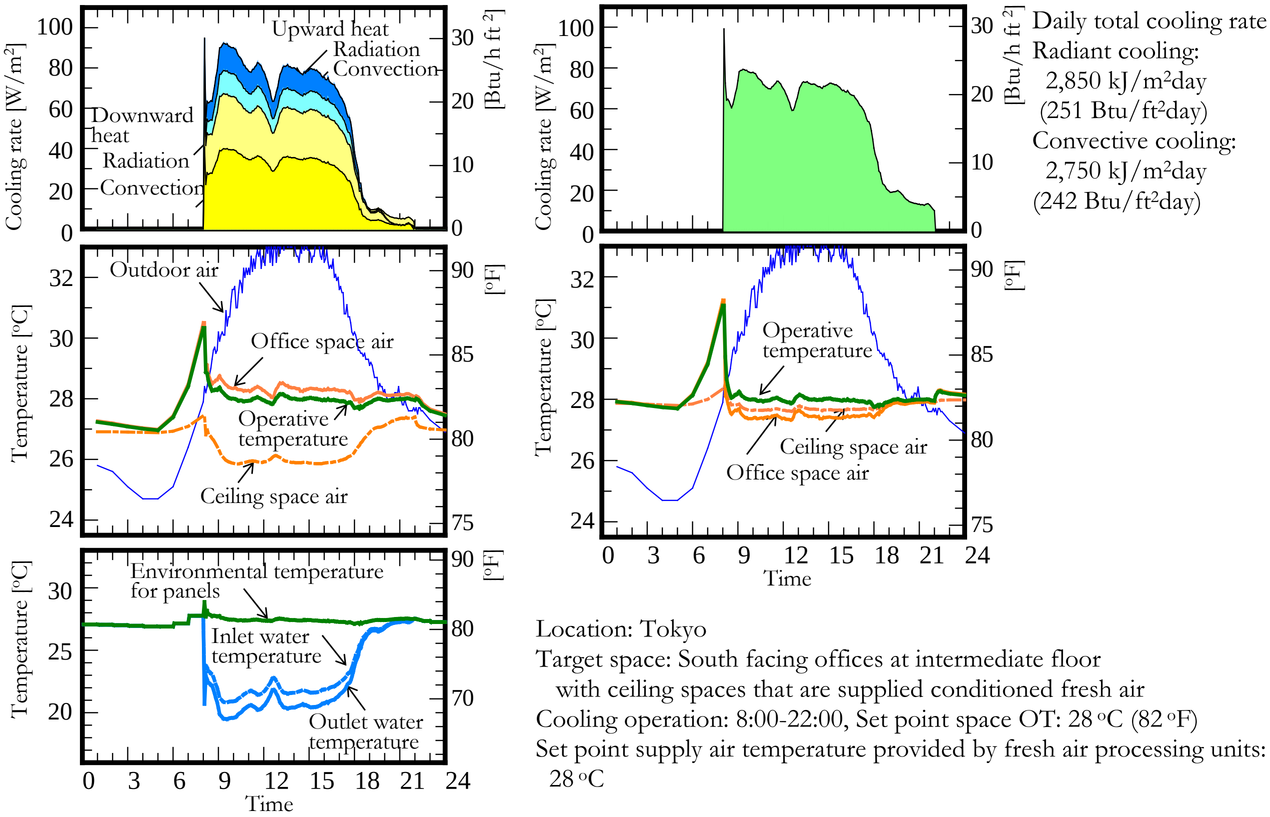
Effect of Radiant Heat Gain

The response of convective heat, Qc, from surfaces surrounding a space to convective and radiant heat gain, HG, through a specific wall can be expressed as the following transfer function:

$$Q_C(s) = W(s) \cdot HG(s) \qquad \dots (6)$$

where W is a weighting function related to radiant delay and is derived using the transfer functions of heat flux for all surfaces (Y. Matsuo 1984). For the inverse transform of Oc, Qc is approximated by a second-order transfer function using Matsuo's optimization method (Y. Mastuo 1983).

Transmitted solar radiation and other internal radiation from heating or cooling devices are assumed to be absorbed by the designated surfaces. The effects of absorbed radiation, which is converted to equivalent air temperature, can be considered in the calculation of heat transfer through walls. Therefore, the tool is applicable to radiant cooling and heating simulation. Figure 2 shows the space environment and cooling rate for radiant cooling by ceiling panels and for convective cooling by FCUs obtained through integrated simulations. Thermal comfort can be evaluated based on operative temperature, which is simply calculated using AST rather than MRT.



Daily total cooling rate
Radiant cooling:
2,850 kJ/m²day
(251 Btu/ft²day)
Convective cooling:
2,750 kJ/m²day
(242 Btu/ft²day)

Location: Tokyo
Target space: South facing offices at intermediate floor
with ceiling spaces that are supplied conditioned fresh air
Cooling operation: 8:00-22:00, Set point space OT: 28 °C (82 °F)
Set point supply air temperature provided by fresh air processing units:
28 °C

Figure 2 Cooling rate and thermal environment in offices in which the operative temperature is controlled on a summer day. (left) Case of cooling by ceiling panels. (right) Case of cooling by FCUs.

Window systems

The tool can be used to evaluate the performance of window systems such as AFWs and DSFs. AFWs are used for exhausting space air, and DSFs can be naturally ventilated while cavity air is overheated by solar radiation. Practical equations for the overall coefficient of heat transfer, $U_{V,m}$, solar heat gain coefficient, $SHGC_{V,m}$, and cavity air temperature, $t_{V,m}$, for window systems were theoretically derived. For window systems with multi-story cavities, the values for the mth story can be obtained using the following equations for the given values of airflow rate, V, outside temperature, t_{Oe}, inside temperature, t_{Re} and solar radiation, I, incident on the surface. The values of other parameters, ΔU, $\Delta SHGC$, T_O, T_{SR} and K_C, are provided in the window system database.

$$U_{V,m} = U_0 + \Delta U \cdot r^m \qquad \ldots (7)$$

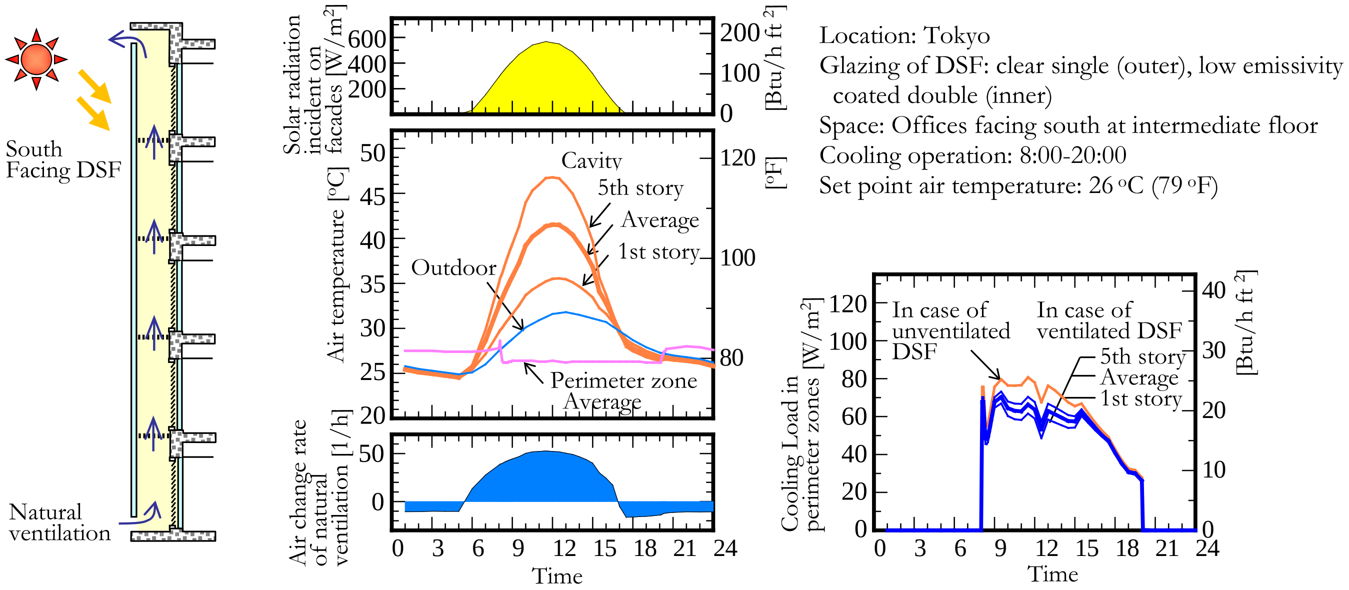
$$SHGC_{V,m} = SHGC_0 + \Delta SHGC \cdot r^m \qquad \ldots (8)$$

$$t_{V,m} = t_{IN} + \{T_O(t_{Oe} - t_{IN}) + (1 - T_O)(t_{\mathrm{Re}} - t_{IN}) + T_{SR} I\}(1 - r^m) \qquad \ldots (9)$$

$$r = c_p \rho V / (K_C + c_p \rho V) \qquad \ldots (10)$$

Heat and airflow balances for naturally ventilated DSFs can be solved using equation (9) and a simple equation for cavity airflow balance.

The simulation results for a summer day for a building with a multi-story DSF are shown in Figure 3. The difference in the ventilated cavity air temperature between the top and bottom stories is approximately 10 K (18 F), and the cooling load reduction by natural ventilation is 12% for the top story zone, whereas that for the bottom story zone is 25%.



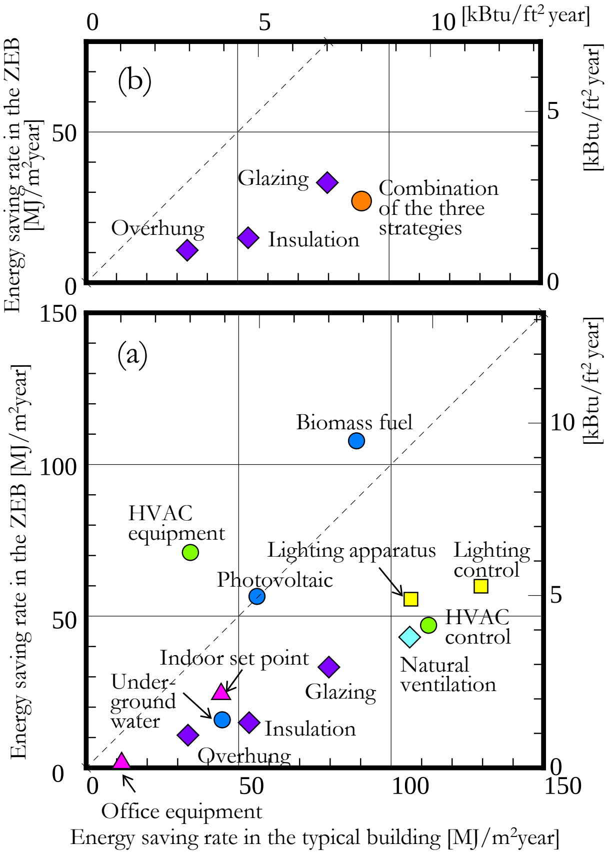
Location: Tokyo
Glazing of DSF: clear single (outer), low emissivity coated double (inner)
Space: Offices facing south at intermediate floor
Cooling operation: 8:00-20:00
Set point air temperature: 26 °C (79 °F)

Figure 3 Cooling load of the perimeter zones in a DSF building. (left) Target DSF, including a five-story cavity. (center) Air temperature and natural ventilation rate in the cavity. (right) Cooling load in the perimeter zones

INTERACTION EFFECTS BETWEEN ENERGY SAVING STRATEGIES

The effectiveness of a specific energy-savings strategy cannot be expected to be the same for all buildings. The energy savings expected for a net zero-energy building (ZEB) differs from that expected for a low-performance building, which is an important consideration in planning a ZEB. The tool can predict energy consumption considering such interactions.

Figure 4 shows the simulation results for the energy saving rates of two buildings. The energy saving rate for a typical building is defined as the energy reduction achieved by adding an energy-reduction strategy, and that for a ZEB is defined as the energy increase achieved by removing the strategy employed in the ZEB. Although many strategies provide significantly lower energy savings for a ZEB than for a typical building, a few strategies are more effective for the ZEB. The combined effects of some strategies are not always greater than the individual effects of adopting only one of the strategies, as shown in Figure 4(b).



Loacation: Osaka
Building: A city hall, five-story; total floor area 7,200m² (77,500 ft²)

(Strategies)
For facades
Glazing; emissivity coated double glazing
Overhung; with horizontal overhungs
Insulation; Insufficient insulation of walls and roofs
Natural ventilation;
For HVAC systems
HVAC equipment; high efficient equipment
HVAC control; VAV, high efficient VWV, fresh air control
For Lighting;
Lighting apparatus; LED lighting
Lighting control; integrated lighting and daylighting control
For Renewable energy
Undergroung water; Undergroundwater source heat pump
Baiomass fuel; wood chip boiler
Photovoltaic; onsite (rooftop) and offsite photovoltaic
For efficient operation
Indoor set-point; Set point indoor air temperature and humidity for energy efficiency
Office equipment; Power saving computers

Figure 4 Energy saving effects of strategies for a typical building and a ZEB. (a) Individual effects of various strategies. (b) Individual and combined effects of strategies for facades.

CONCLUSION

The simulation methods used in the tool enable integrated energy simulations as well as conventional and practical thermal load simulations. The thermal performance of window systems, such as AFWs and DSFs, can be simulated while considering the effects of vertical temperature distributions in ventilated cavities. The tool has the ability to evaluate energy and environmental performances considering the interactions between several elements of buildings and systems.

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NOMENCLATURE

A_k = coefficient in an equation of indicial response of the wall

c_P = specific heat of air

I = solar radiation incident on the façade surface

$k0$ = number of roots of a transfer function

$R_{k,n}$ = common ratio for an exponential term

r = efficiency factor of ventilation in the cavity

$SHGC_V$, $SHGC_0$ = solar heat gain coefficient of ventilated DSF and that of unventilated DSF

t_{IN}, t_{Oe}, t_{Re} = inlet air temperature for ventilation, outside and inside temperature of the DSF

U_V, U_0 = overall coefficient of heat transfer of ventilated DSF and that of unventilated DSF

V = ventilation rate

$X_{k,n}$ = coefficient for R

$Z_{k,n}$ = transient term ($Z_{k,0}$ =0)

α_k = root of transfer function

ΔT_n = time interval between the time step n-1 and the time step n

φ = response factor of heat absorption into the wall

θ = inside or outside temperature of the wall

ρ = density of air

Subscripts

n = current time step

k = exponential term number

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