ENERGY SIMULATION OF RESIDENTIAL HOUSES USING EESLISM

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ABSTRACT

EESLISM is a tool developed to simulate the whole energy system consisting of both building thermal system and mechanical system for heating and cooling and domestic hot water supply. Although the algorithm is based on the heat balance model, the algorithm is designed to reduce the size of simultaneous equations for increasing computation efficiency and simplification in developing software. The simulation results can be used also to examine the heating and cooling system demand, since the imaginary components for generalized heat load simulation of the system are prepared. As an example the simulation of a multi family house with a central type of space and water heating system is described.

INTRODUCTION

In order to design energy efficient buildings it is important to predict the performance of total environment control system consisting of both building fabric and mechanical system. Since using building thermal mass, radiant heating and cooling systems and passive and active solar heating systems are the examples of the technologies which are expected to be used for energy efficient buildings. In designing the whole building simulation, algorithm using the heat balance model is considered as the most useful method, however, the disadvantage of the heat balance model to be required for solving a set of huge simultaneous equations at each time step of the simulation process was pointed out [1].

The author has been developing the algorithm and the tool EESLISM since 1990 to simulate the whole energy system consisting of both building thermal system and mechanical system for heating and cooling and domestic hot water supply which is especially important for the energy simulation of residential houses [2-5].

EESLISM has been developed using C language on UNIX workstations. EESLISM can simulate room thermal environment, heat loads of room and equipment and energy used by space heating and cooling systems and domestic hot water systems. The features of the EESLISM are as follows;

1) Although the algorithm is based on the heat balance model consisting of a set of heat and moisture balance equations of the all components used in the system to be simulated, using the component equation concept the algorithm is designed to reduce the size of simultaneous equations for increasing computation efficiency and simplification in developing software.

2) Except for final design stage, specifications of equipment are not often decided and heat loads of heating and cooling coils and plants may be one of the purposes of simulation. In such case the heat loads of the coils and plants can be simulated under the pre-designed system control scheme, therefore, EESLISM can be useful from early stage of system design to final stage of the design.

3) As the implicit type of finite difference method is used for the unsteady state heat calculation, a time step interval in the simulation can be selected from 1 minute to 1 hour depending on the object of the simulation. Short time step may be useful to examine the thermal performance of domestic hot water systems or the control strategy of the heating and cooling systems and 1 hour time interval may be usually used for the annual system simulation.

SYSTEM STRUCTURE

System Components

The system components included in EESLISM are as follows; room including radiant heating and cooling panels, cooling and heating coil, boiler, heat pump, solar collector, heat storage tank, pipe, duct, fan, pump, heat exchanger, header, and imaginary heating and cooling component. Table 1 shows the system components prepared in the current version of EESLISM.

Fig. 1 shows an example of a CAV system for two rooms. The pipes and ducts are not included for simplification as an example. Table 2 shows the system components of the model shown in Fig. 1. Each system component of the simulation model corresponds to a system component of the real system. A room is also defined as a system component of the simulation model.

Table 1 System components prepared for EESLISM 4.5

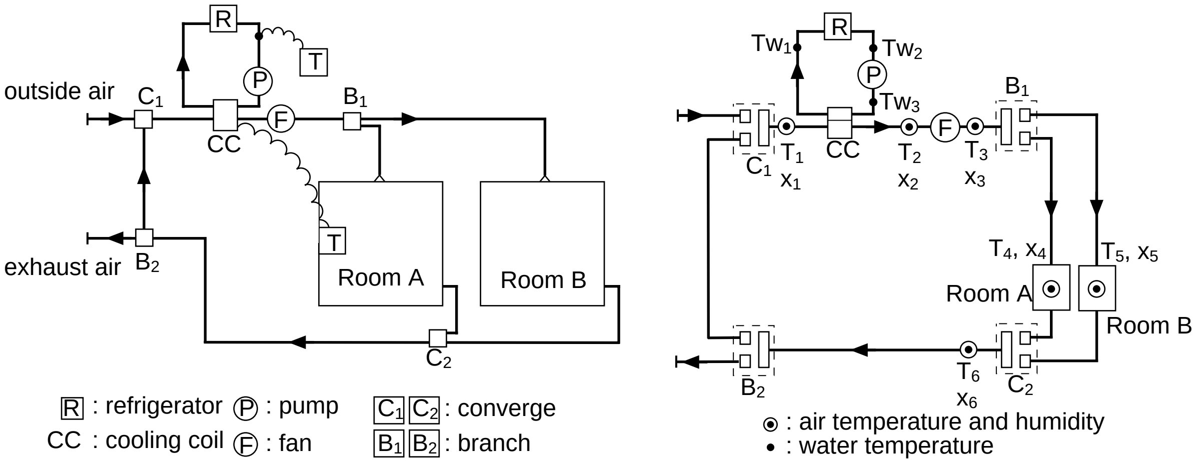
Component	Type	System variables	Internal variables	Mathematical model
BUILDING				
Room	P	Tr, xr	room surface temperatures wall temperatures	heat balance model finite difference for wall heat conduction
Radiant panel	P	Tout	inside temperature	(a part of room thermal model)
EQUIPMENT				
Heating/ Cooling coil	P/A	Taout, xaout Twout		temperature and enthalpy effectiveness
Package AHU	A	Taout, xaout	evaporating temp. condensing temp.	temperature and enthalpy effectiveness
Heat storage tank	P	Twout	water temperatures of tank	multi-node of fully mixed block
Heat pump	A	Tcout, Thout	evaporating temp. condensing temp.	linear approximation of compressor
Boiler	A	Twout		boiler efficiency
Solar collector	P	Twout		steady state heat balance model
Heat exchanger	P	Thout, Tcout		steady state heat exchange model
Pipe	P	Twout		steady state heat loss model
Duct	P	Taout		steady state heat loss model
Header (converge)	P	Twout		mean of inflow air
Header (diverge)	P	-		(none)
Converge duct	P	Taout, xaout		mean of inflow water
Branch duct	P	-		(none)
Fan	P	Twout		steady state heat gain
Pump	P	Taout		steady state heat gain
IMAGINARY COMPONENT				
Heating/ cooling coil	A	Taout, xaout, (Twout)		Eqs. (7), (8) and (9)
Heating/ cooling plant	A	Twout		Eq. (10)

A: active component, P: passive component
System variables T: temperature, x: humidity ratio
subscripts r: room a: air w: water h:hot side c: cold side out: outlet in: inlet

System Variables and Internal Variables

In order to reduce the size of the simultaneous equations expressing the whole heat and moisture balance, the temperatures and the humidities of each components are classified into two categories, a system variable and a internal variable. Generally, the system variables are inlet and outlet temperatures and humidities of working fluid flowing through the system components. Room air temperature and humidity are defined as the system variables. Examples of the internal variables are the inside temperatures of components such as water temperatures of a heat storage tank, condensing and evaporating temperatures of a heat pump and room surface and wall temperatures of a building. The internal variables and system variables are not independent each other originally, however, arranging the original heat balance equations for each system components with sophisticated algebraic operations, the heat balance of the system components can be expressed without the internal variations as described in the later section. The internal variables are calculated using the system variables after solving the system equation.

The system variables are used in the component equations to express the heat or moisture balance of the system components. The system equation is a set of simultaneous equations consisting of the component equations. As each component equation can be arranged to express the heat or moisture balance of a component with only the system variable(s), the size of the simultaneous equation is limited to the maximum number of the total system variables in which the internal variables are not included.



a) Schematic diagram b) Simulation model

Figure 1 Example of CAV System

Table 2 System components of example CAV system shown in Fig.1

component	name in model	number of system eqs. for each component	system variable	related flow path
room	RoomA	2	T_4, x_4	PathA
	RoomB	2	T_5, x_5	PathA
cooling coil	CC	3	T_2, x_2, Tw_1	PathA and PathW
fan	F	2	T_3, x_3	PathA
branch duct	B_1	-	-	PathA
	B_2	-	-	PathA
converge duct	C_1	2	T_1, x_1	PathA
	C_2	2	T_6, x_6	PathA
chiller	R	1	Tw_2	PathW
pump	P	1	Tw_3	PathW
Total number		15	15	

PathA: cold/hot air flow path PathB: cold/hot water flow path

For example, the system variables of the system in Fig. 1 are the air temperatures and humidities, T_1 to T_6 and x_1 to x_6 and the water temperatures, Tw_1, Tw_2 and Tw_3. Each system variable corresponds to the outlet temperature or humidity of the component. Room air temperature and humidity are not outlet variables of the components, while they are defined as the system variables. As it is assumed that the temperature or humidity is constant when the air or water flows through the branch as expressed B_1 or B_2, the outlet variable of the branch component is not necessary to include in the system variable, while, the outlet temperature or humidity from a converging component such as C_1 or C_2 is a system variable. Since the outlet temperature or humidity is defined as the flow rate weighted mean of the inlet conditions of the inflow fluid.

The total number of the unknowns as the system variables is 15 which equals to the number of the component equations. Therefore, solving the simultaneous equations of the component equation, the system variables, temperatures, humidities of the system components are obtained , then the internal variations and the heat gains or losses and energy consumptions can be calculated.

Active Components and Passive Components

In order to clarify the control strategy and to design the related algorithm, the system components are categorized in two types, active component and passive component. The heating or cooling output of the active component can be controlled under the designed scheme, while the passive component can not be controlled. As shown in table 1 the examples of the active component are heating or cooling plants such as boilers, refrigerators and air handling units. Examples of the passive components are pipes, ducts, heat storage tanks, heat exchangers and solar heat collectors. The room is defined as passive component. In addition, the heating or cooling plants at the maximum capacity operation are considered as the passive components as the heating or cooling amount is not controlled to modulate the capacity.

As one of the active components, it is useful to define the imaginary component which behaves as a heating or cooling plant or a heating or cooling coil without detailed specifications of the component.

ALGORITHM OF SYSTEM COMPONENTS

Room Thermal Model

The room thermal model used in EESLISM is based on the implicit type of finite difference method for the calculation of unsteady state heat conduction of building envelopes except for windows. For the simulation model of room surface heat transfer, radiation and convection are calculated separately. While multi-room model considering the thermal behavior of adjacent rooms is used, avoiding large matrix consisting of all the building thermal elements, sophisticated algebraic operations are used to conduct room thermal model using the system variables and the internal variables [6-9].

Eq. (1) shows the total heat balance of the room air conducted from the basic equations. Eq. (2) shows the moisture balance model of room air which is used with the room thermal model for the simulation of room air humidity and latent heat load [2, 9]. The coefficient RMT_{ij} and the constant term RMC_i are conducted from the heat balance equations of the room air, the room surfaces and inside of the walls using algebraic operations. RMT_{ij} includes all the heat transfer processes which are the radiative and conductive heat transfer at the room surfaces and heat conduction in building envelopes and partitions. RMC_i also includes all the heat transfer processes as well as the effects of the internal heat generation and external weather condition.

RMX_i and $RMXC_i$ are the coefficient and the constant term conducted from only a moisture balance equation of the room air, since the moisture transfer through building envelopes is ignored.

$$\begin{aligned}&\sum RMT_{ij} \cdot Tr_j - caGvo(Ta - Tr_i)\\ &-\sum caGvr_{ij}(Tr_j - Tr_i) - Qd_i = RMC_i\end{aligned} \quad (1)$$

$$\begin{aligned}&RMX_i \cdot xr - Gvo(xa - xr_i)\\ &-\sum Gvr_{ij}(xr_j - xr_i) - Ld_i = RMXC_i\end{aligned} \quad (2)$$

(i=1,2, ..., Nroom)

$$Qd_i = caGd_i(Td_i - Tr_i) \quad (3)$$

$$Ld_i = Gd_i(xd_i - xr_i) \quad (4)$$

Qd_i and Ld_i express heat supply and moisture supply rate, respectively, which are also expressed by Eqs. (3) and (4) when the room is conditioned by supplied air. The negative value of Qd_i or Ld_i means the heat or moisture extraction rate. Radiant heating and cooling systems using water or air can be also included in the room thermal model [3].

Equipment

Basically linear model is used for the system component model of the equipment. For the system component with one flow path, the component equation is expressed using a inlet temperature and a outlet temperature of the working fluid flowing through the component as shown in Eq. (5).

$$Q = D_0 - D_1 \cdot Tin = cG(Tout - Tin) \quad (5)$$

For multi-flow path component with Nin of inflow and Nout of outflow paths, Eq. (6) can be conducted from the basic mathematical model for each system component. Examples of multi-flow path component are heat exchanger with two flow, heat pumps and heat storage tanks.

$$\sum_{n=1}^{Nin} a_{m,n} \cdot Tin_m + b_m \cdot Tout_m = c_m \quad (6)$$

(m = 1, 2, …,Nout)

The coefficients of the system equations, D_1, $a_{m,n}$ b_m and the constant terms D_o, c_m are conducted from the mathematical model of the equipment [4,10].

Modelling of Control System

Two kinds of control modelling, real and imaginary processes are considered. The real control model is used for simulate the real control process such as On/Off or the proportional control in which control scheme is explicitly defined and modelled. The imaginary control model assumes an ideal control process in which the object component is controlled to maintain the set point without real control scheme. Any combination of controlled object and a set point can be accepted as far as the control scheme is rational.

Imaginary Components and Heat Loads

In order to simulate the heat loads of heating and cooling coils or plants, the imaginary components are prepared as the system components. The imaginary component should be the active component which can be controlled. Using the imaginary components heat loads can be simulated without detailed specification of the coils and plants for heating or cooling, while the whole system consisting of system components and flows of water and air and control scheme has been designed. The heat load simulated using the imaginary components can be considered as extension of the room heat load which is calculated under the implied conditioned of air type of heating and cooling system combined with ideal control system to maintain the room air temperature at a set point. In Fig. 1 the air temperature of ROOM A is a set point and controlling object is a heating coil output.

For an imaginary cooling coil, sensible and latent heat balances are shown with Eqs. (7) and (8), respectively.

$$Qloads = cGa(Taout - Tain) \qquad (7)$$

$$Qloadl = rGa(xaout - xain) \qquad (8)$$

Eq. (7) shows only the definition of the sensible heat load and the heat load can not be calculated with only Eq. (7), since the inlet and outlet temperatures, Taout and Tain are unknown in most cases. However, combining Eq. (7) with other system components and solving the simultaneous equation describing the whole system to be simulated, the heat load, Qloads can be calculated.

In case of water coil, Eq. (9) is necessary to express air and water heat exchange. For a dry coil Eq. (8) is deleted, since the humidity is constant through a coil

$$\begin{aligned} Qloadt &= cGw(Twin - Twout) \\ &= cGa(Taout - Tain) + rGa(xaout - xain) \end{aligned} \qquad (9)$$

For an imaginary component model for a heating or cooling plant is expressed with Eq. (10).

$$Qload = cGw(Twout - Twin) \qquad (10)$$

When the chiller and the cooling coil in Fig.1 are assumed to be the imaginary components the following simulation process can be considered.

1) Assuming the cooling coil is controlled to maintain the room air temperature and humidity of ROOM A and the outlet temperature of the chiller is set to be a scheduled set point.

2) Among all the system variables in Table 2, the chilled water temperature, Tw_2 and the room air temperature T_4 and x_4 are removed from the unknown system variables. However, sensible and latent heat loads Qloads and Qloadl are added to the unknown variables. Thus, the total number of the unknown is 14.

3) As the system variable related of the chiller, Tw_2 is a known value, the system equation of the chiller is not need to include for the system equation. Therefore, the total number of the system equations is 14. Solving the simultaneous equations of the system equations the heat loads of the coil are calculated with other system variables.

As humidity is not often controlled in cooling systems, the constant outlet relative humidity model can be used

Table 3 Structure of input data

COMMON DATA	
TITLE	title, comments
GDAT	simulating period, selection of output files and weather data file
VCFDATA	time series data used for boundary conditions or control conditions
SCHTB, SCNHM	schedule data
EXSRF	definition of surface tilted angle and azimuth to be used for building data and solar collector
BUILDING DATA	
WALL	structure of walls, floors, ceilings and roofs
WINDOW	window data
SUNBRK	definition of sun breakers attached to building surfaces
ROOM	definition of room using floor and surface areas and elements defined in EXSRF, WALL, WINDOW and SUNBRK
RESI	occupants data
APPL	appliances data including lighting
VENT	ventilation and infiltration data
EQUIPMENT DATA	
EQPCAT	catalogue data for equipment
SYSCMP	definition of system components using ROOM and EQPCAT data
FLOW PATH DATA	
SYSPTH	air flow and/or water flow path data according to the system schematic diagram and definition of allocation of system components on the paths
CONTROL DATA	
CONTL	set points, detecting points and controlled objects

to simulate the free floating humidity ratio of the cooling system. In the simulation using the imaginary components, the temperature difference between heat source and the load is not considered similar to expressing the cooling plant load as the simple total of the coil loads.

SIMULATION TOOL

Structure of Input Data

Input data are composed of the descriptions of building and system components, relationships between components and control schemes of the system. The input data are shown in Table 3. The input data are described using the free formatted text data consisting of key characters, key words and name of components and necessary numerical data.

Definition of Flow Path

Air or water flow paths and allocation of the system components on the paths are defined using the schematic diagram of the system as shown in Fig. 1. As shown in Table 2 the definitions of flow paths and system components are described at the different part of the data input process in order to allow the system components such as heat exchangers connected to more than one path. The relationships among the system variables to be used for setting up the simultaneous equation describing the whole system can be found from the flow path data.

System Equation and Energy Calculation

At each time step during the system simulation process, a system equation is set up and solved. The system equation is a set of simultaneous equations consisting of heat and moisture balance equations of all the components in the system. Solving the system equation, the system variables are obtained. The heat loads of the imaginary components are also obtained. Then, using the system variables, the internal variables such as room surface temperatures, wall temperatures and water temperatures in the heat storage tanks are calculated. The heat gain and heat loss of the system components can be also calculated depending on requirements. Energy consumptions are calculated using the system variables and the internal variables of the components which use electricity, city gas or oil.

EXAMPLE SIMULATION OF A MULTI FAMILY HOUSE

Using EESLISM the simulation of various type of energy efficient houses has been carried out [11, 12]. Figs. 2 to 5 show the application to a multi-family house with 30 housing units [13]. The whole house is provided with a central type of space and domestic hot water heating system using hot water. Fig. 2 shows the schematic diagram [13]

Using the standard weather data of Tokyo the hour by hour simulation was carried out throughout a year. The total number of the system variables is 238, while the total number of the temperature nodes including both the system variables and the internal variables is 1425. This example shows that the system component method is very effective to reduce the size of the simultaneous equation consisting of the heat balance equations. Using the imaginary components, the heating coil load for the space heating of each housing unit was simulated, while the hot water heating for each housing unit was simulated with the two flow paths heat exchanger model. The boiler was considered as an imaginary component and the boiler heating load was simulated using a constant hot water supply temperature. The room air temperatures are supposed to be controlled using the operative temperature expressed with a mean of a room

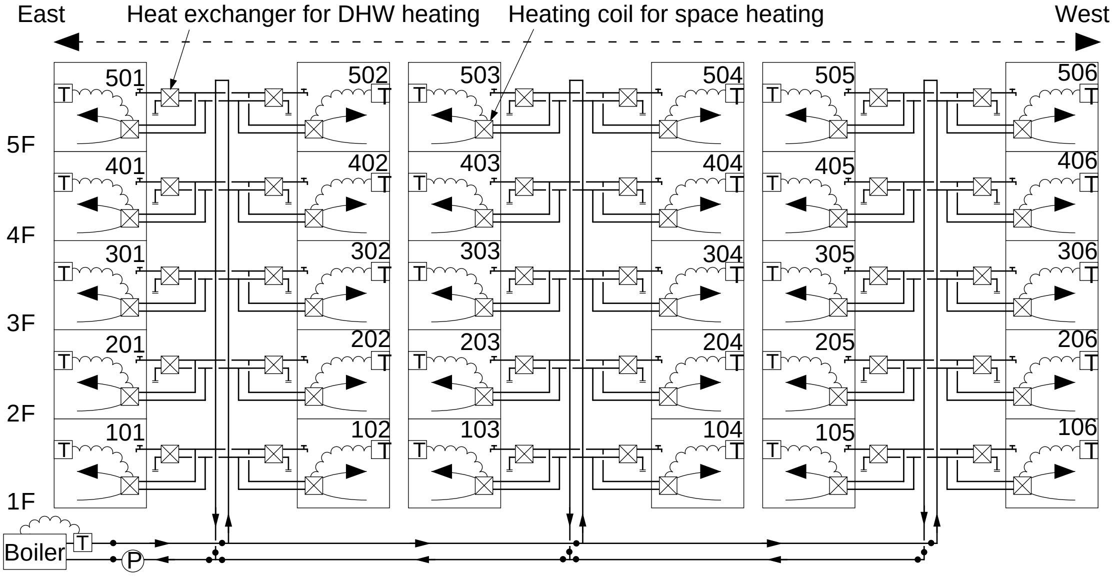
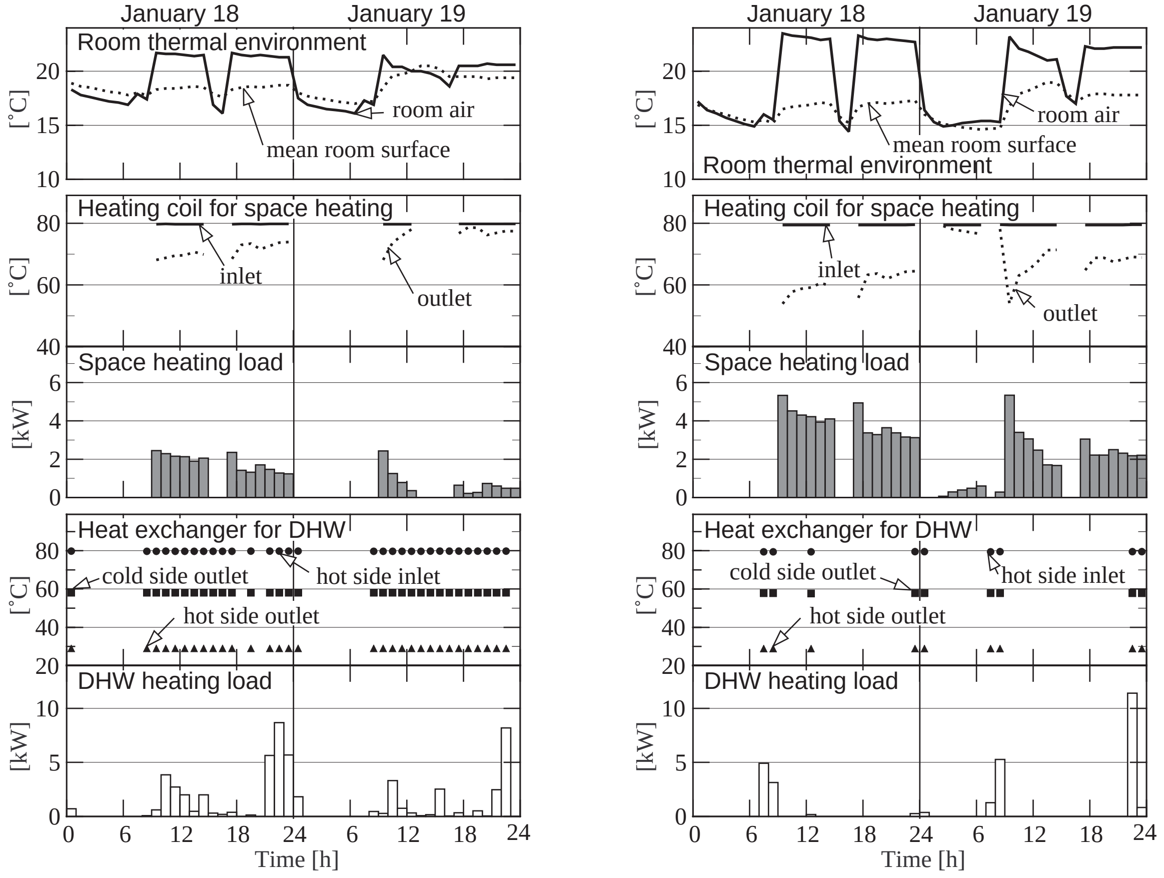
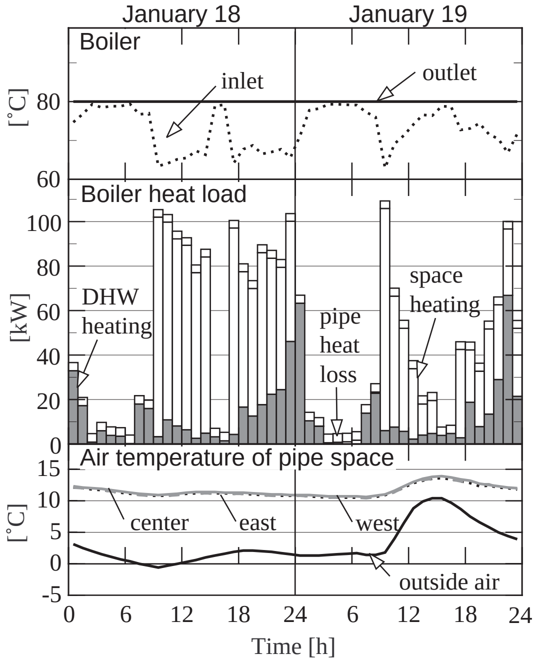


Figure 2 Central heating system of a multi-family house used in example simulation



a) Central housing unit (304)

b) Top-west corner housing unit (506)



c) Heating Plant

Figure 3 Example results of hourly variation on the typical winter days

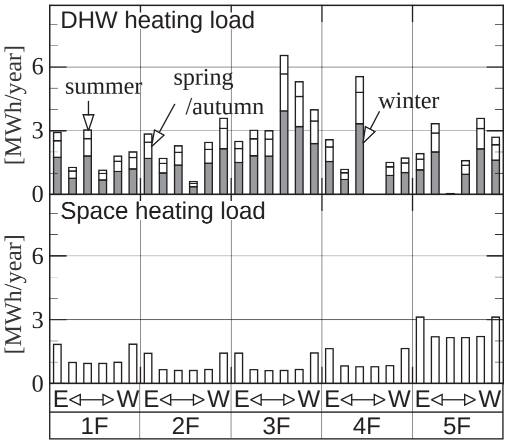


Figure 4 Annual space and DHW heating loads of housing units

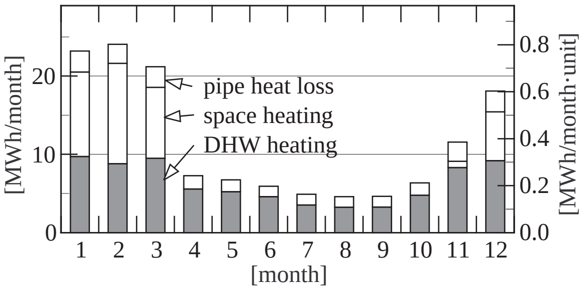


Figure 5 Monthly variation of space and DHW loads of heating plant

air temperature and a mean room surface temperature. In Figs. 3a and 3b, while the room air temperatures during heating hours are different from the housing units, the operative temperature is the set point, 20 degrees C for both the houses. Fig. 4 shows the annual space and hot water heating requirements for each housing unit. Fig. 5 shows the monthly variation of total heating load of the whole house.

SUMMARY

The features of a whole building simulation tool, EESLISM is described.

Although the algorithm is based on the heat balance model consisting of a set of heat and moisture balance equations of the all components used in the system to be simulated, using the component equation concept the algorithm is designed to reduce the size of simultaneous equations for increasing computation efficiency and simplification in developing software.

The idea of the imaginary component is useful to examine the heating and cooling capacity of the equipment without the detailed specifications of equipment. This is useful to use the simulation results for the system design.

In order to demonstrate the application to a large scale energy system, the simulation results of the central space and hot water heating system for the whole multifamily house were described.

While the example simulation describes the application of EESLISM to the residential house, EESLISM is useful to simulate both residential and non residential buildings.

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NOMENCLATURE

T: temperature, ˚C
Tr: room air temperature, ˚C
Ta: outside air temperature, ˚C
Tw: water temperature, ˚C
x: humidity ratio, kg/kg
xr: room air humidity ratio, kg/kg
xa: outside air humidity ratio, kg/kg
ca: specific heat of air, J/kg K
cw: specific heat of water, J/kg K
G: flow rate, kg/s
Gvo_i: ventilation rate of room *i*, kg/s
Gvr_{ji}: air change rate between room *j* and room *i*
Gd_i: conditioned air supply rate to room *i*, kg/s
Ld: moisture supply rate by conditioned air, kg/s
Q: heat supply rate, W
Qd: heat supply rate by conditioned air, W
Qload: heat load, W
r: latent heat of water vaporization, J/kg

subscripts
i, j: room i and room j, respectively
a: air
w: water
in: inlet
out: outlet
s: sensible heat
t: total heat
l: latent heat