

# THERMAL AND AIRFLOW NETWORK SIMULATION PROGRAM NETS

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## ABSTRACT

Based on the thermal and airflow network model with simple but perfect generic formulations and stable solving methods, a computer program NETS for the practical simulation of coupled building heat, gas and air transfer system has been developed. NETS can simulate the feedback or the schedule control on models' structural changes and various driving condition changes. A pre-processing system called NETSGEN and a post-processing system called NETSOUT have been also developed. NETSGEN enables designers to freely construct the thermal and airflow network model on energy saving new ideas with an ease of simply drawing a picture. NETSOUT graphically displays the computed results. NETS is versatile and especially suitable for use in research, development and design of passive and low energy architecture.

## INTRODUCTION

A simulation program for thermal and airflow systems in buildings using thermal and airflow network models called NETS is being developed. The program has high degrees of freedom and generality, and provides a tool for designers and developers of building facilities and designs to investigate new concepts by flexible simulations. The main part of the program named NETS, which has been developed using Fortran language for over 10 years, originally aimed at simulating passive solar houses. In some passive solar houses, heat flow is controlled by varying airflow paths and opening of heat insulating panels according to the time zones, seasons, and ambient temperature. This means that the model structure varies with scheduling and feedback controls, and NETS is suited for simulating such variation. Preprocessing and postprocessing programs, which are named NETGEN and NETOUT respectively, are also being developed in these two years, and the total system is called the NETS system. This paper describes features of the simulation models, outline of the calculation theory, outline of the preprocessing and postprocessing programs, and some applications of this simulation program that make use of the characteristics of this simulation program.

## FEATURES OF THE THERMAL NETWORK SIMULATION MODEL

The mathematical model of the thermal network[1] relates to what is called the heat capacity nodal system that is obtained by the spatially discretizing method, and all heat transfer forms between node  $i$  and node  $j$  by conduction, radiation, convection, and mass flows are expressed by a single kind of parameter  $c_{ij}$  called generalized thermal conductance. The heat balance at a node is defined by what is called a nodal equation of perfectly connected system assuming that each node is thermally connected with all other nodes as shown in the equation below. In this equation,  $x_i$  is the temperature of node  $i$ ,  $m_{ij}$  is the heat capacity of node  $i$ ,  $c_{ij}$  is the generalized thermal conductance from node  $j$  to node  $i$ ,  $g_j$  is the  $j$ th heat source of the total number  $ng$ , and  $r_{ij}$  is the ratio of heat that flows from  $g_j$  to the  $i$ th node;  $no$  is the total number of the nodes that have known temperature values such as the outside air temperature, and  $n$  is the total number of nodes having unknown temperature values.

From this nodal equation of perfectly connected system that holds generally regardless of the spatial dimension or shape of the calculation objects, the following ordinary differential equation of vector

$$\sum_{j=1}^n m_{i,j} \cdot \dot{x}_j = \sum_{j=1}^{n+no} c_{i,j} \cdot (x_j - x_i) + \sum_{j=1}^{ng} r_{i,j} \cdot g_j$$

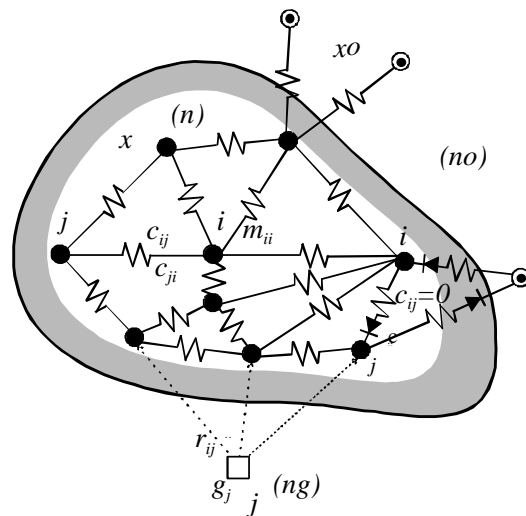


Figure1. Concept of thermal network

matrix is derived for the system of total capacity nodes. This equation is called a state equation after the terminology of applied mathematics of the system theory.

$$M \cdot \dot{x} = C \cdot x + Co \cdot x_o + R \cdot g$$

Only system parameters  $c_{ij}$ ,  $m_{ij}$ ,  $r_{ij}$ , and the model sizes  $n$ ,  $no$ , and  $ng$  change with the objects of calculation. If the system parameters that are not zero are given, those system parameters that are not given automatically become zero. These are the reasons why the computing programs for constructing the unified equation and solving the ordinary differential equation have complete generality. While space discretization is usually done by the finite volume method, even when the finite element method is partially applied, a scheme has been devised to make it possible to calculate the total system as a whole using the above-mentioned equation model by combining the partial models constructed by these different methods. This scheme involves the improvement of formulation relating to the boundary conditions of the conventional finite element method and the definition of subscripts for the system parameter[1].

Simulating the variation of state values such as temperature with time leads to time integration of the ordinary differential equation. While all of the varieties of conventional time integration methods give only approximate solutions, the author has proposed a strict solution, which is called analytical time integration method by projective decomposition[1]. However, this strict solution requires the eigenvalue analysis of system matrix, and it is usually difficult to quickly obtain exact eigenvalues of large system matrices. Therefore, approximate time integration has to be used from a practical point of view, and the stability of calculation is the most important factor for this approximation. This is because conditions imposed

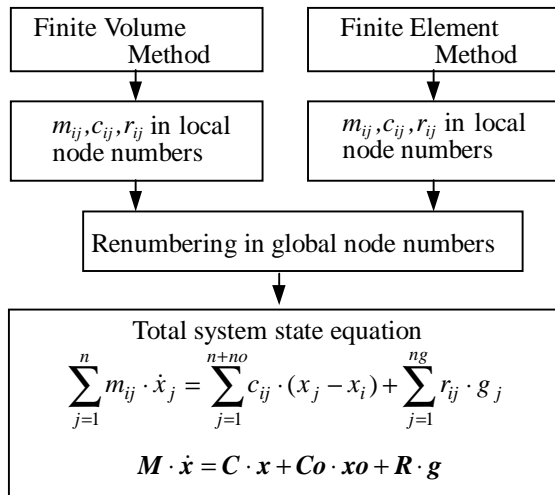


Figure 2. Unification of different spatial discretization models

on spatial or time discretization to obtain stability increase calculation time and the main memory capacity, thereby often deteriorating practicality. NETS often uses the complete implicit method (backward difference). Further, to decrease the volume of the inverse matrix calculation of the system matrix in this method, it is applicable to approximately calculate the inverse matrix by dividing the rows, and it is also possible to improve the computer economy by reducing the practical number of nodes making use of the condensation theory of the state equation[1]. In the future, this condensation method may solve the problem of excessive increase in the number of nodes when the spatial automatic mesh division is applied.

### FEATURES OF THE AIRFLOW NETWORK SIMULATION MODEL

The airflow network[1] basically consists of two models elements, zones and flow paths. Even when a branched duct system exists, the model elements are reduced to these two by assuming zones at the branch points. This generalization, however, requires the modeling concept that the static pressure at the bottom of a zone is assumed as the total pressure including dynamic pressure. So the author call this

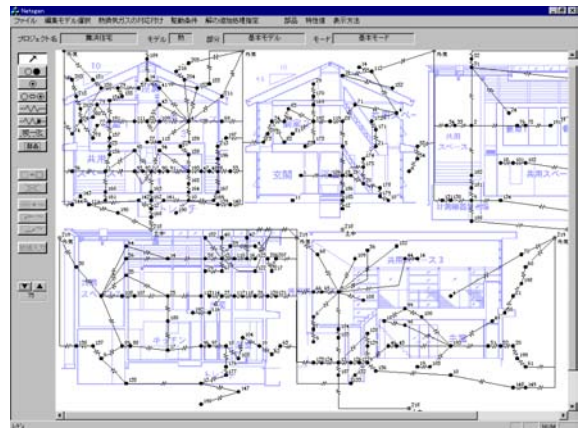


Figure3. Thermal network model

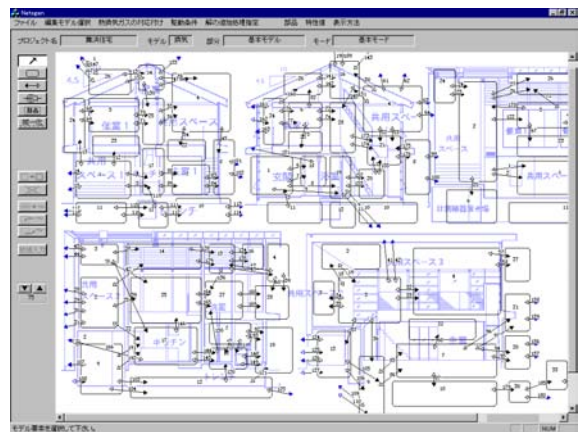


Figure4. Airflow network model

model a total pressure nodal system[1]. The mathematical model may as well be a linear simultaneous equation system that is constructed at each step in the process of repeated calculation applying the pressure assumption method. This is a simultaneous equation system by the vectors of the total pressure and the Jacobian matrix relating to these vectors. NETS defines an array of the total pressure node (zone) numbers in the up stream side of the flow path and those in the down stream side in order to construct the equation system using simple algorithm and data structure. In the calculation of airflow balance, the algorithm[1] is made simple by indirect addressing appropriate total pressure node (zone) numbers by this array of numbers. The author has also elucidated the mechanism of vibration generated in the normal Newton-Raphson method and proposed a modified Newton-Raphson method.

**DRIVING CONDITIONS**

Driving conditions refer to the conditions that drive the model, and include meteorological conditions such as outside air temperature and solar radiation, artificial conditions such as temperature, calorific value, gas concentration, gas generation, as well as structural and parametric variations of the model

itself. These driving conditions are executed by schedule and also by feedback control. The structural and parametric variation of the model itself is called mode change[1]. For example, it refers to disconnection or change in value of generalized thermal conductance in the thermal network, and changes in opening area, pressure loss coefficient, and blower speed in the airflow network. The mode change is defined individually and independently after several subsets are defined in the universal set of the model elements, and is controlled specifically

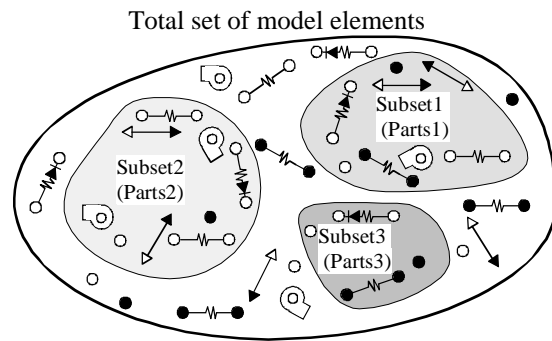


Figure5. State of mode in each parts

Sub-process	Thermal Network Model	Airflow Network Model	Gas Flow Network Model
<b>Characteristics of materials</b> Conductivity, Discharge coefficient, etc.	<b>Model elements</b> 		
<b>Finite Element Method</b> 	<b>Partial model</b>  (ex.)Heat exchanger	 (ex.)One floor of bldg.	 (ex.)Wall
<b>Model Condensation</b> 	<b>Subsystems</b> 		
<b>Driving conditions</b> Mode change Feedback control Daily schedule Periodic schedule	<b>Coupled total system</b>  Nodal relation among subsystems		

Figure6. Pre-processor NETSGEN outline

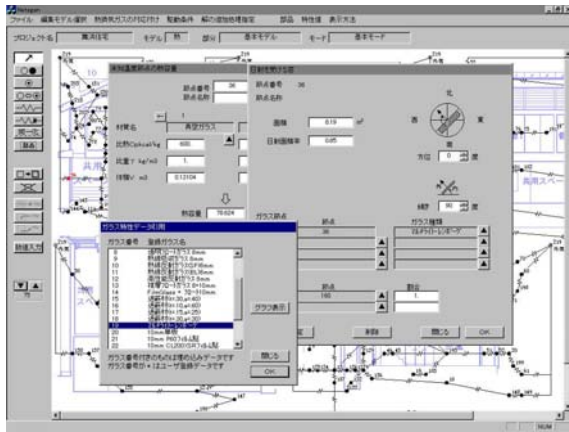


Figure7. Solar parameters for glass windows

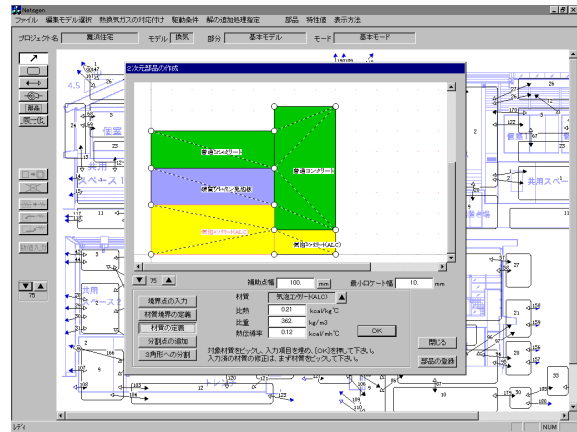


Figure10. Parts by two dimensional FEM

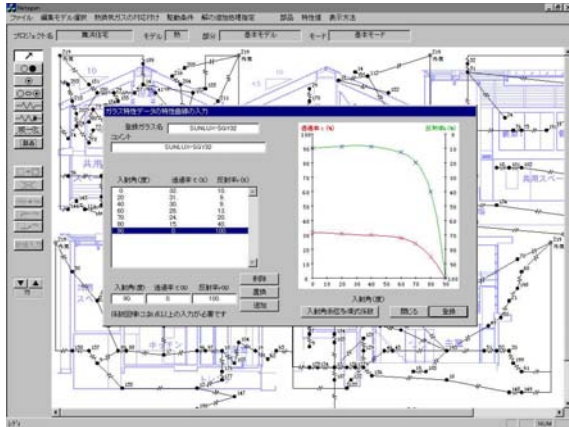


Figure8. Transmittance and reflectance of glass

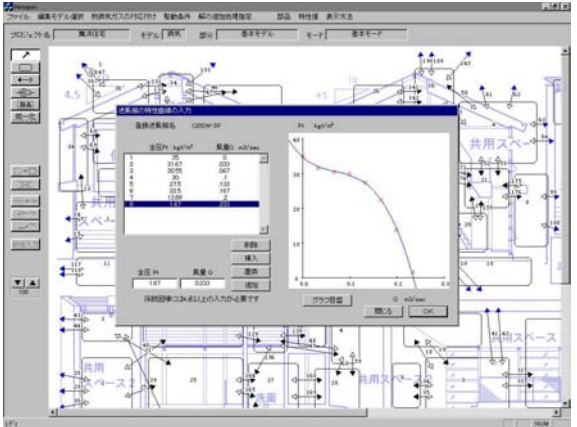


Figure11. Fan P-Q characteristics curve

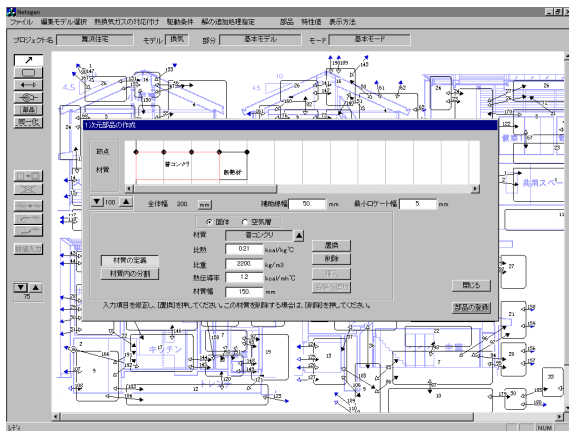


Figure9. Wall parts by one dimensional FEM

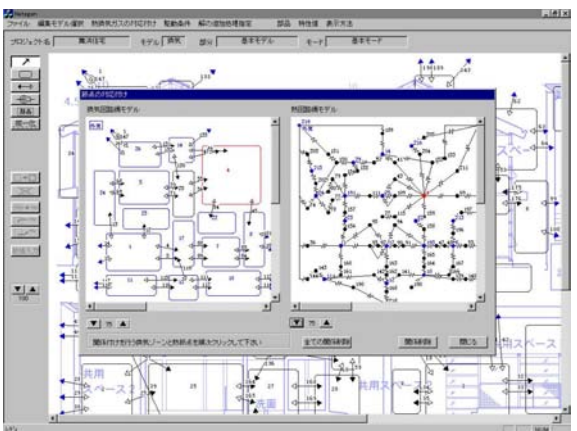


Figure12. Nodal relation thermal and airflow network model

by parts and mode number of each part. These parts refer to the aforementioned subsets and do not necessarily mean spatial parts. The driving conditions are controlled by schedule with a concept of daily patterns. For example, the daily pattern of ordinary days differs from that of holidays. The daily pattern defines changes in modes and system parameters, artificial conditions, and feedback control. Several patterns of these conditions in a day are prepared as daily patterns, and a table that sets the sequence of these daily patterns is defined as the sequence definition table. The feedback control rule is defined as a procedure from detection quantities to operational quantities. The above-mentioned mode numbers are included in these operational quantities. The daily pattern for implementing the feedback rule is also defined, and PID control is possible as a means of feedback control. The PID control is effective for solving the problem of the delay in time integration between the measurement of detection quantities and control operation in this simulation, which is not so in the actual phenomena. It is also effective for handling the situation where the functional relationship between the operational

quantities and control quantities is unknown. The time integration interval is taken from the minimum of one minute to the maximum of one hour. Since the meteorological data are taken at the intervals of one hour, the gap is linearly interpolated. NETS also can calculate air conditioning situations under the room temperature constraint in the same way as the usual thermal load calculation. In this case, changes in the node numbers and the size of the state equation are automatically executed since nodes treated as unknown temperature nodes change to those of known temperature.

### PRE-PROCESSING AND POST-PROCESSING SYSTEMS

The model structure of NETSGEN can be designed based on a CAD diagram. Stereotyped parts that are frequently used can be registered in the library so that the model design efficiency is improved. Because the mathematical models of this thermal network are compatible with the finite element models, models for walls etc. can be made by the linear finite element method and stored as parts. Two-dimensional finite element model can be also made and incorporated

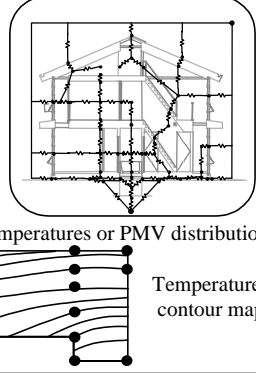
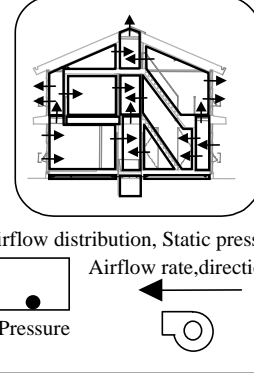
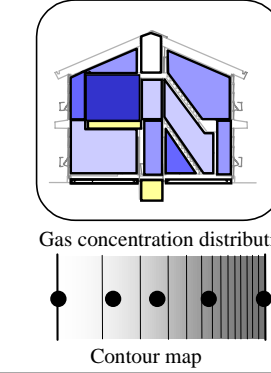
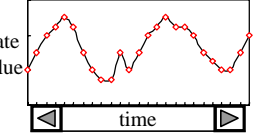
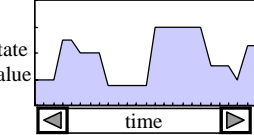
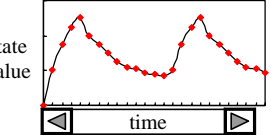
<b>State of mode in each parts</b>	<table border="1" style="display: inline-table; margin-right: 20px;"> <tr> <td>Parts number</td> <td>0</td> <td>1</td> <td>2</td> <td>3</td> <td>4</td> <td>5</td> <td>6</td> </tr> <tr> <td>Mode number</td> <td>1</td> <td>1</td> <td>3</td> <td>1</td> <td>1</td> <td>2</td> <td>1</td> </tr> </table> Parts means not only partial model but also subset of model elements			Parts number	0	1	2	3	4	5	6	Mode number	1	1	3	1	1	2	1
Parts number	0	1	2	3	4	5	6												
Mode number	1	1	3	1	1	2	1												
<b>State of operation in each control rule</b>	<table border="1" style="display: inline-table; margin-right: 20px;"> <tr> <td>Control rule number</td> <td>1</td> <td>2</td> <td>3</td> <td>4</td> <td>5</td> <td>6</td> <td>7</td> </tr> <tr> <td>ON/OFF</td> <td>OFF</td> <td>OFF</td> <td>ON</td> <td>ON</td> <td>OFF</td> <td>OFF</td> <td>ON</td> </tr> </table> Control rule means calculation process from sensor node to manipulator node			Control rule number	1	2	3	4	5	6	7	ON/OFF	OFF	OFF	ON	ON	OFF	OFF	ON
Control rule number	1	2	3	4	5	6	7												
ON/OFF	OFF	OFF	ON	ON	OFF	OFF	ON												
	<b>Thermal Network Model</b>	<b>Airflow Network Model</b>	<b>Gas Flow Network Model</b>																
<b>Spatial distribution of state variables</b>	 <p style="font-size: small;">Temperatures or PMV distribution Temperature contour map</p>	 <p style="font-size: small;">Airflow distribution, Static pressure Airflow rate, direction Pressure</p>	 <p style="font-size: small;">Gas concentration distribution Contour map</p>																
<b>Time sequence of state variables</b>	 <p style="font-size: small;">State value time</p> <p style="font-size: small;">Temperature Thermal load Heat generation</p>	 <p style="font-size: small;">State value time</p> <p style="font-size: small;">Airflow rate Static pressure Blower flow rate</p>	 <p style="font-size: small;">State value time</p> <p style="font-size: small;">Gas concentration Gas removal Gas generation</p>																

Figure13. Post-processor NETSOUT outline

into the total model prepared by other finite volume method. The parts library function is also available for the airflow network. For the blower, both fixed air quantity and variable air quantity that varies according to the cubic curve of P-Q characteristic can be applied, and the blower can be installed in an arbitrary flow path. After the model structures of thermal and airflow networks are designed, model elements such as node, generalized thermal conductance, zone, and flow path are clicked to open the dialog, and values are defined. Mode changes are defined by partially modifying the diagram of the basic model. NETS stores the parameters of these change differences. The correspondence of node numbers among the thermal, airflow, and gas flow network models can be related intuitively by comparing two of the diagrams for these models. Driving conditions can be flexibly defined by clicking the elements in the model diagram without any consideration to model element numbers such as node number.

NETSOUT displays simulation results in two general types: one is spatial distribution displays relating to state values such as temperature, gas concentration, room pressure, air quantity, PMV, and thermal load;

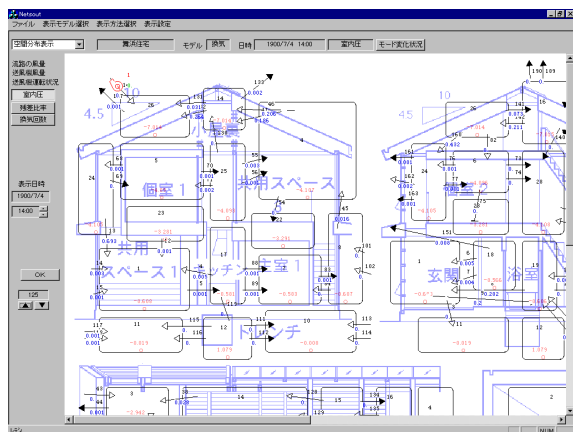


Figure 14. Results of airflows and space pressures distribution

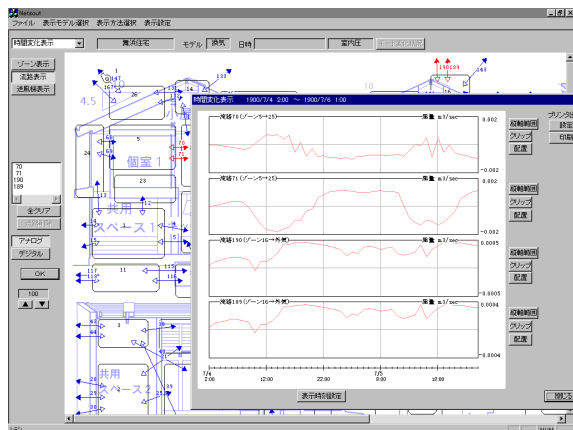


Figure 15. Results of airflow rate time sequence

and the other is time series displays of these state values. The situation of mode changes and feedback control can also be confirmed. Spatial distribution of state values is displayed, in principle, by numerical values in the neighborhood of model elements. Change of state values with time is displayed on a graph with the abscissa showing time sequence, and values at a desired time is obtained by scrolling the abscissa.

### EXAMPLE OF APPLICATION TO HEAT STORAGE IN STRUCTURES

NETS was applied for investigating a method to level the electricity load by reducing the cooling load during the daytime making use of the heat storage in building structures at night. In this method, change over dampers are installed in both suction side and discharge side of the ceiling mounted air conditioner so that air is attracted not only from the room but also from the ceiling plenum, and sent not only to the room but also to the ceiling plenum. Since each damper has two modes of airflow, there are 2 by 2=4 modes in total. These four modes are called the heat accumulation mode, the heat discharging mode, the radiation cooling/heating mode, and the normal air

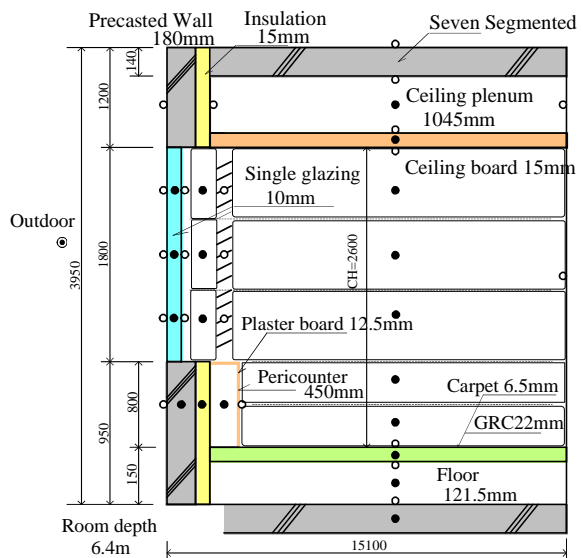
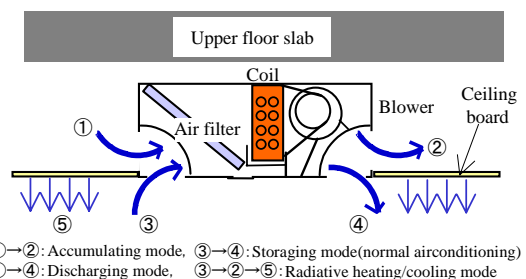


Figure 16. Building structure thermal storage Office building section



①→②: Accumulating mode, ③→④: Storing mode (normal airconditioning)  
①→④: Discharging mode, ③→②→⑤: Radiative heating/cooling mode

Figure 17. Air conditioner with four modes

conditioning mode respectively. In the radiation cooling/heating mode, air is blown into the ceiling plenum to cool or heat the ceiling boards aiming at an additional air conditioning effect by radiation.

As an example of investigation, a plane of 6.4m by 15.1m of a standard office building was simulated.

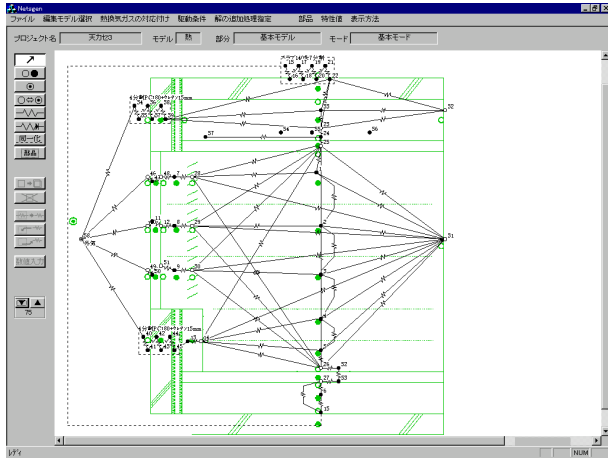


Figure18. Building structure thermal storage thermal network model

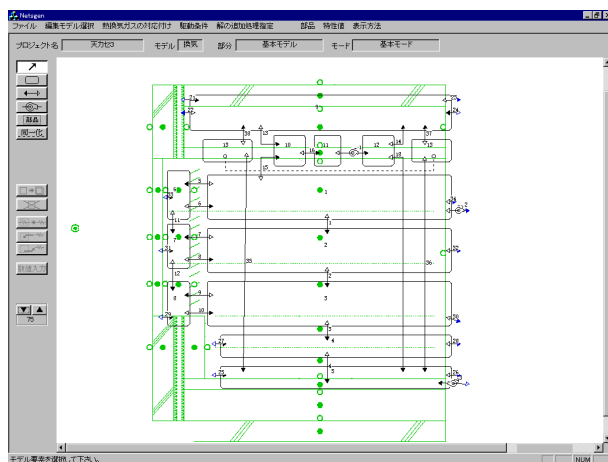


Figure19. Building structure thermal storage airflow network model

Table1. Simulation conditions

<ul style="list-style-type: none"> <li>·Occupants 0.1 person/m<sup>2</sup></li> <li>·Heat generation by occupants:70W/person</li> <li>·Heat generation by apparatus:17W/m<sup>2</sup></li> <li>·Heat generation by lighting:23W/m<sup>2</sup></li> <li>to ceiling plenum 30%, to room 20%, to floor surface 50%</li> <li>Where internal heat gen. is reduced to 50% 12:00-13:00</li> <li>·Outside air intake:5m<sup>3</sup>/h·m<sup>2</sup></li> <li>System operating schedule</li> <li>·Thermal accumulating period:22:00-8:00</li> <li>·Pull down period:8:00-9:00</li> <li>·Air-conditioning period9:00-20:00</li> <li>·Stopping period:20:00-22:00</li> </ul>
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Figure 16 shows its sectional drawing. The room space together with the air layer between the windows and blinds was divided in the vertical direction based on the concept of zonal model. Floor slabs were divided into seven segments in the normal direction. When the office is closed, the airflow is caused by natural draft and varies depending on the temperature difference between the inside and outside of the building etc. Figures 19 and 18 show diagrams for airflow network model and thermal network model respectively. In the model, the box of ceiling mounted air conditioner was divided into three portions, i.e. air inlet portion, coil portion, and air outlet portion. Zones were allocated also to the gaps in the ceiling boards. In the thermal network model, slabs and outside walls were taken into the total model constitution after constructing parts by the linear finite element method. Radiation heat transfer among the inside surfaces of the room was modeled being separated from the convection components. The standard meteorological data of Tokyo for the dynamic thermal load calculation was used and nine days from July 25 to August 2 was made an approach run period. Figure 20 shows the variation of room temperature, temperature in the ceiling, mode change, and the change in internal heat generation on August 4 and 5. The numerical figures in the figure show the time when the change in the mode and internal heat generation took place. During the one hour for pull down (from 8 to 9 o'clock), intake of outdoor air was suspended. However, heat removal was not necessary during this period due to the cool storage during night, and the heat load occurred only after the internal heat generation became large.

Simulations were made for the cases in which the heat removal flow in the coil was PID controlled aiming at: 18degC and 23degC for the temperature in the ceiling plenum, 26degC for the air temperature in the zone 1.1m above the floor, and 0 PMV in the same zones. The PID control was applied because of the fact that the control quantities and operational quantities were separately located in the space, in addition to the effect of PID control described in

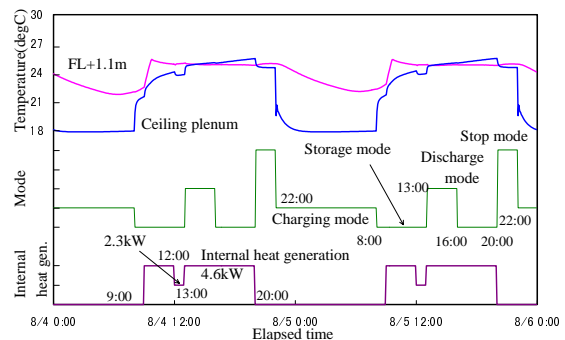


Figure20. Mode change and internal heat generation

"DRIVING CONDITONS". Figures 21 and 22 show the results for the case in which PMV is controlled to 0 instead of controlling the room temperature. It is shown that the room temperature becomes lower than 26degC in this case.

By totaling the heat removal flow, the ratio of the load that has been shifted from day to night (peak shift ratio) due to the storage in structures compared with the normal cooling load without heat storage, and the heat loss by the heat storage (heat storage loss ratio) were calculated. Table 2 summarizes the evaluation indices from August 3 to August 5. These results show that the peak shift ratio is higher than

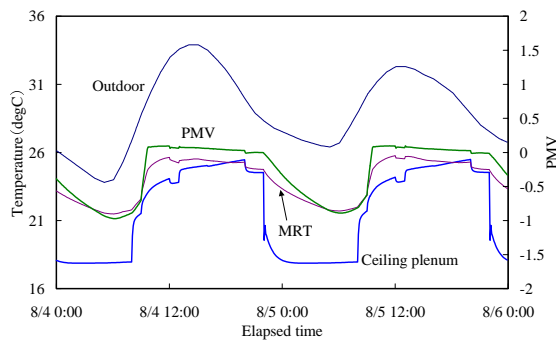


Figure21. Temperatures and PMV

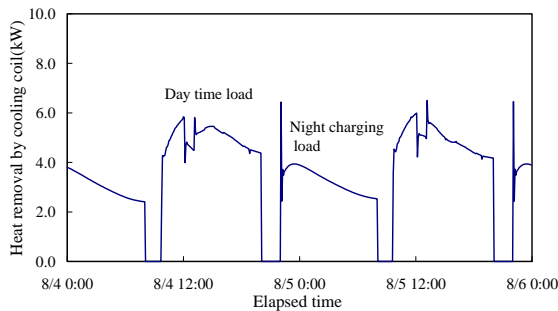


Figure22. Thermal loads

Table2. Building structure thermal storage performance computed results

In case of using night storage (control PMV to zero in occupied space) [MJ]						
	Night time load : A	Day time load : B	Daily load : C	Reducing ratio : D	Heat loss ratio : F	Stored heat in slab : G
Control target	Plenum-chamber to 18°C	PMV to 0				
Aug. 3	113.1	153.4	266.6	0.401	0.041	73.8
Aug. 4	116.8	183.8	296.9	0.357	0.038	74.1
Aug. 5	116.8	183.4	300.2	0.362	0.044	73.6
Control target	Plenum-chamber to 23°C	PMV to 0				
Aug. 3	45.4	215.0	260.5	0.160	0.017	31.1
Aug. 4	45.3	245.0	290.3	0.143	0.015	31.3
Aug. 5	48.6	245.1	293.7	0.148	0.021	30.8

In case of using no. storage (intermittent air-conditioning)

	Night time load	Day time load : E	Daily load : E
Control target	-	PMV to 0	
Aug. 3	0	256.0	256.0
Aug. 4	0	286.1	286.1
Aug. 5	0	287.7	287.7

1. On-peak load reducing ratio :  $D=(E-B)/E$
2. Storage heat loss ratio :  $F=(C-E)/E$
3. Stored heat in slab :  $G=\text{sum}(\text{temperature decrease in slab} \times \text{thermal capacity})$
4. Daily thermal load :  $C=A+B$

35% and the heat storage loss ratio is about 4% when heat is stored with the target temperature in the ceiling at 18degC. When heat is stored with the target temperature of 23degC, the peak shift ratio is about 15% and the heat storage loss ratio is about 2%. For the investigation of such new concepts as mentioned above, creation of new simulation programs or addition to or revision of existing programs has been required. However, the NETS system has been proved to be generally applicable because of its generality of the models and driving conditions.

### ACKNOWLEDGEMENTS:

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### CONCLUSION

Among the many existing models for heat transfer and airflow in buildings that apply spatial discretizing and formulation, the author's thermal and airflow network models can be proposed as general, universal and simple ones. For the time integration method of the thermal network model, simple and unified numerical formula and a most accurate method have been proposed. For the airflow network also, simple and unified structure of model data and a stable solution have been shown. Further, a preprocessing system that makes use of the generality of the model is described. This model can be flexibly applied to the investigation of new heat transfer structures. A concept to handle the structure change of model called the mode change has been introduced, and the results of investigation on the effect of heat storage in building structures have been described as an example of application and verification of the concept. The structures of the proposed thermal and airflow network models are compatible with conventional models making standardization and unification possible.

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