BUILDING THERMAL NETWORK MODEL BASED ON STATE-SPACE SYSTEM THEORY

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ABSTRACT

The development history of three theories on predictive calculation, system identification and optimum control methods using a thermal network model by the first author are described. It is important to note that a state-space approach based on system theory underlies these three theories. Special focus is placed on a history of the predictive computation program NETS development, and a number of significant features are described. Further, this paper provides results of a cooperative case study as computed by NETS on a multi-functional ventilation system that takes advantage of stack effects particular to a multi-layer building.

INTRODUCTION

When computer simulating building heat transfer and airflow, microscopic models such as computational fluid dynamics often encounter difficulty in tackling large heat transfer systems with multi-chamber and longer-term calculations that take into consideration thermal capacity. Therefore, macroscopic models constructed by using engineering knowledge become useful. The thermal and airflow network model is a sort of macroscopic model and is suitable for investigation of a total building and systemic problems. In addition, formulation of the thermal network provides a framework including these micro and macroscopic models. This paper first introduces the research and development history by the first author for these models, and further, a case study describes the application of the simulation program carried out in cooperative research.

Table1 Basic mathematical formulations

Perfectly connected nodal equation for Conservation's Law, e.g. heat flow balance.

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

Thermal network model State-Space equation

$$\mathbf{M}\cdot\dot{\mathbf{x}} = \mathbf{C}\cdot\mathbf{x} + \mathbf{C_o}\cdot\mathbf{x_o} + \mathbf{R}\cdot\mathbf{g} \qquad (2)$$

Time integration by projective decomposition on eigenspaces (NETS) (3)

$$\mathbf{x}(t) = \sum_{i=1}^{n}\mathbf{P}_i\cdot e^{\alpha_i\cdot(t-t_0)}\cdot\mathbf{x}(t_0) + \int_{t_0}^{t}\sum_{i=1}^{n}\mathbf{P}_i\cdot e^{\alpha_i\cdot(t-\tau)}\cdot\mathbf{f}^*(\tau)d\tau$$

Performance index of optimal control (SOCS)

Quadratic function constituted of deviations of states and inputs vectors from references

$$J_c = {}^t(\mathbf{x}-\mathbf{r})\cdot\mathbf{W_x}\cdot(\mathbf{x}-\mathbf{r}) + {}^t(\mathbf{u_c}-\mathbf{d})\cdot\mathbf{W_c}\cdot(\mathbf{u_c}-\mathbf{d}) \qquad (4)$$

is minimized for states and control inputs vectors

Criteria for system parameters identification(SPID)

Quadratic function of error with observation equation integrated over the measurement period

$$J_i = \int_0^T {}^t\mathbf{e}\cdot\mathbf{W}\cdot\mathbf{e}dt \qquad (5)$$

is minimized for system parameters : $m_{i,j}, c_{i,j}, r_{i,j}$

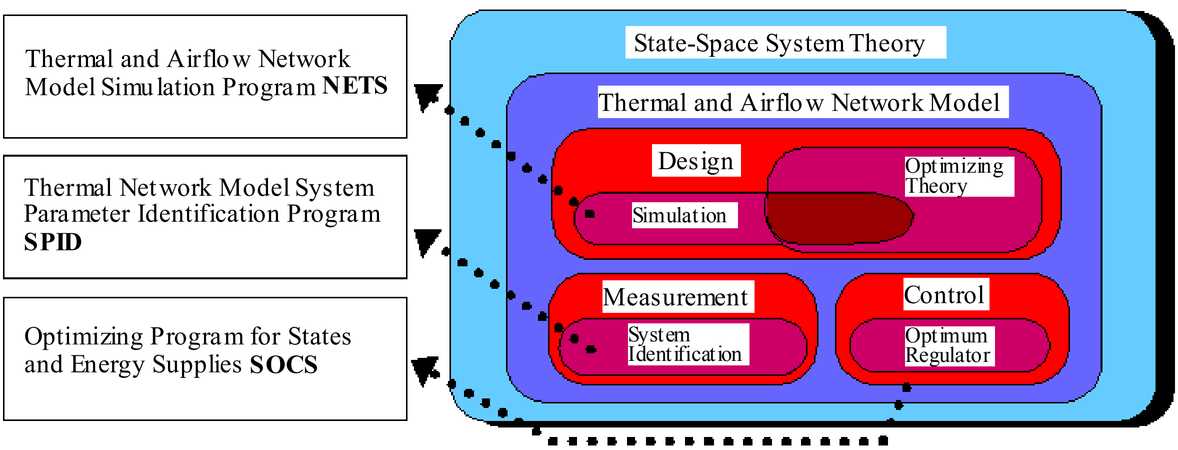

Figure1 Theories and computer programs

BACKGROUND THEORY

When the thermal network model was started to predict the actual heat transfer phenomena as being very similar to the electrical network, that had almost same meaning for all researchers. But for the thermal network model by the numerical computation, many different thermal network models were proposed concerning the formulation and the solution. For example, the models by Dr. Clarke J. A.[1] and Dr. Edward F. Sowell[2] were presented in the former conference BS'99 and are well known.

Whereas, the thermal network model described in this paper has been developed owing to the various persons as being described in the next section for the history. For the characteristic of this model, the state-space method of applied mathematics should be mentioned as the background theory. In the various engineering fields, there had been applied the optimum control theory based on the state-space method, the system identification theory and the optimal design theory. In order to apply easily these abstract theories for our fields, the formulation method and solution of this model has been devised.

As shown in Table 1, by devising the perfectly connected nodal equation (1), the general state equation (2) could be composed evidently. The process leading to the exact solution of state equation (3) also made it possible to study the mathematical structure of diffusion system and the numerical stability. In the next section, as the historical circumstances being described, the equation's error applied for the criteria (5) of system identification utilizes the error of state equation (2). Moreover, the performance index (4) and the solution of optimum control was led by referring to the optimum regulator control, but the versatility of optimizing calculation program was realized by the formulation of (1) and (2). These predictive calculation, system identification and optimum control computation program, as shown in Figure 1, are respectively called NETS, SPID and SOCS. In the practice, it is inadequate to be only able to do the predictive calculation, so the model should be provided for the disposition as a platform of these three theories, because of many requests which might accompany with the system identification, optimum control and optimal design.

HISTORY OF THEORETICAL DEVELOPMENT

The study and development of thermal network models started around 1975 to achieve computational prediction for passive solar house thermal performance. For the nodal equation that represents heat balance, The first author was inspired by a computational model for a solar collector disclosed in a research report [3] filed by the Solar Energy Laboratory of the Wisconsin University with the US federal government in 1972. The temporal integration scheme adopted initially, although an approximate solution based on temporal finite differences, had high stability resulting from complete implicit solution. Initially, however, it was difficult to understand the mathematical grounds for the unconditional stability. A few years later, the nodal equation (1) and the total equation (2) could be represented as a state equation, which enabled the assessment of the eigenvalues characteristics particular to the transition matrix.

The first difficulty in airflow network model development was the phenomena of numerical oscillation which disturbs the stable solution of nonlinear simultaneous equations for room pressures. Beginning at assumed values near the solution allows the Newton-Raphson method to be applied effectively and correctly. In addition, the solution for room pressures is self-evident with no ventilation driving force. Therefore, the early stage solution was a successive incremental approach method with the Newton-Raphson that starts from zero driving force and gradually approaches actual driving force. However, even this method might not offer the solution, and the investigation into the numerical process finally led to the modified Newton-Raphson method.

Around 1977, our field also knew the modern control theory, and one of the books written by Dr. Julius T. Tou[4], discloses an effective state space approach. It was easy to realize for the first author that the thermal network can be represented as a system and calculated by this state equation. Colleagues of the first author, Dr. Tatsuo Shimizu and Dr. Tetsushi Kiyokawa, provided him with helpful advice about the problem with the state equation encompassing temporal integration. The strict solution based on system matrix projective decomposition on eigenspaces denoted by the equation(3) was thus deduced. Moreover, the formulations (1) and (2) enable to derive a general conditional expression and other equations on the stability of several approximate solutions.

The system theory of the thermal network model has been applied successfully to measuring technologies as well. Dr. D. V. Pryor and Dr. C. Byron Winn presented a paper [5] on a sequential filter estimation for determining the thermal characteristics of a passive solar house from measured temperature changes in an actual building. The paper triggered off the development of a generic system identification theory based on the understanding of the essence of the least squares and thorough re-deduction for the thermal network model. A multi-chamber theory[6] presented by Dr. Frank W. Sinden was also a suggestive theory on tracer gas dispersion system and gave us motivation for actual measurement focusing on tracer gas dispersion instead of a temperature diffusion system. Owing to these works we could develop a multi-chamber airflow measurement system that functions as shown in the Figure2.

In 1987, the first author was invited to be a guest researcher by professor Tor-Göran Malmström at the

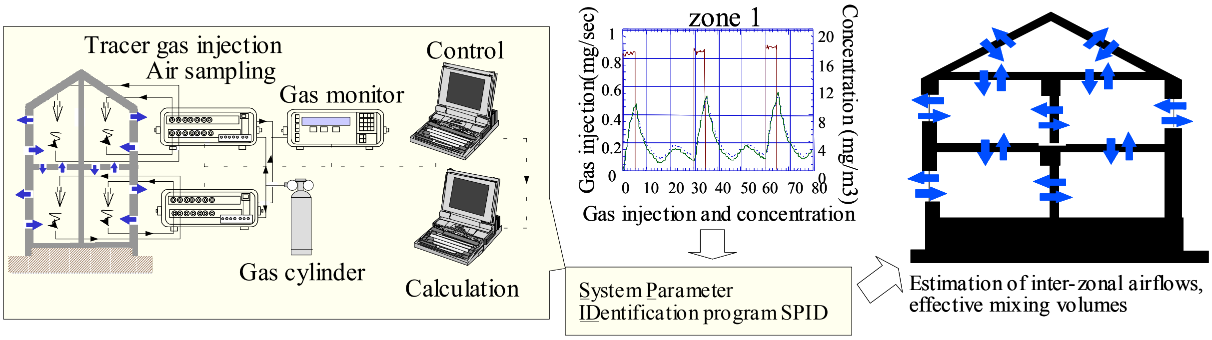

Figure2 Multi-chamber airflow measurement system

building service engineering course of the Swedish Royal Institute of Technology. The first author then proposed an experiment for evaluating this multi-chamber airflow measurement system in the ventilation experiment laboratory[7] operated by Dr. Mats Sandberg of the Swedish National Institute of Building Technology. Dr. Sandberg willingly accepted that proposal for the joint research [8]. Prof. Lars Jensen of Lund University, gave him a useful suggestion that airflow rates to be estimated should be constrained non-negatively and presented a Linear Programming theory [9] for taking account of these constraints. The suggestion has led him to use the non-negative least squares[10] to improve the system identification theory. Through many field applications of the second-generation measuring system the necessity of improvement on the system became clear to allow a distributed device system for gas monitor and air sampling. This is because tubing work needed for the second-generation measuring system prevents its efficient practical application. An experiment for evaluating the second-generation measuring system was carried out in a “cylinder house”[11] designed by Dr. Takao Sawachi of the Building Research Institute belonging to the Japanese Ministry of Construction.

Originally, the state space model was proposed to develop the optimum control theory. Since its solution is expressed as a form of continuous integral equation, actual numerical computation required a modification of the model and the solution. First, as a most common interest the first author tackled a optimum regulator control problem. For the arrangement, a least squares approach using the Costates and Lagrange multipliers solution [12] based on a discrete time system model was useful. Initially, the transient state was treated. However, this solution provided few practical advantages for actual air-conditioning equipment control. Then the possibility of application as the optimum design theory came in sight. Taking it as an extension of the thermal network model, an augmented model coupling heat and water vapor transfer for air-conditioning equipment, human bodies, and a building was developed. The total model has a state vector containing both state variables of temperature and humidity. The criteria of quadratic performance index(4) introduced in the optimum control theory and also in the computaional program SOCS consists of the sum of three terms, thermal comfortableness, energy saving and usable energy saving factors[13]. In particular, the possibility of usable energy saving quantification depends on how close the temperature of heat transportation water is to the outside air temperature. Designing an air-conditioning system with effective energy and usable energy saving can be realized by mathematically solving the minimizing problem of the performance index function(4) for energy supply, and temperature and humidity. The current air-conditioning system design and control overrates air temperature. Also taking a thermal radiation environment and humidity concurrently into account may, however, enable design of an air-conditioning system that features higher

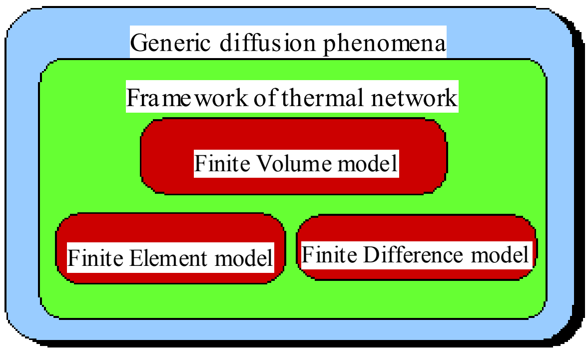

Figure3 Platform for spatial discrete models

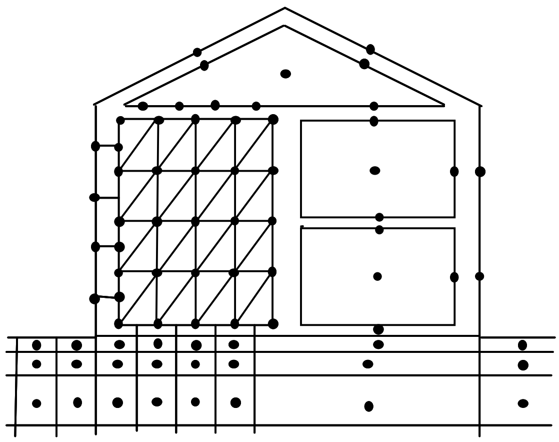

Figure4 Practical modeling by combining different spatial discrete models

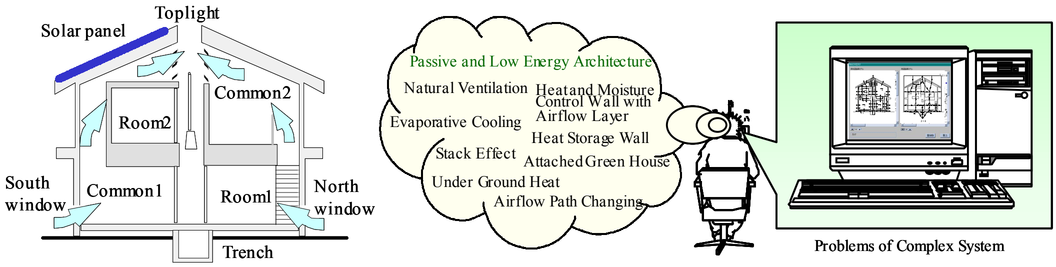

Figure5 Computer simulation system NETS for researcher and designer

energy and resource saving. A case study[13] has revealed that even a much lower hot water temperature is enough for appropriate floor heating, rather than the conventional temperature.

As shown in the Figure3, this thermal network model provides a platform framework covering various types of spatial discrete models also. This means that linking various models can contribute practical and efficient modeling as shown in Figure4. The airflow network model and the computational fluid dynamic model can also be considered simultaneous equation systems for pressures. Therefore, that both models could be linked by implicit and stable formulation instead of being linked by explicit solution in which numerical instability frequently occurs.

DEVELOPMENT OF NETS

The present prediction computation system, NETS, is broken down into a solver part based on the Fortran language and graphic input/output processing parts based on the C language. The outlines of preprocessing program, NETSGEN, and post-processing program, NETSOUT, have been introduced in the previous paper[14].

Development of the NETS was triggered by a request from the department of health physics of the Japan Atomic Energy Research Institute to create a program to predict effects of radioactive protection. This request was made around 1982 to investigate the impacts of a nuclear power plant accident on nearby residential buildings. Computing the phenomena of radioactive materials invading houses and buildings called for computing air infiltration using an air flow network. Further, taking account of the influence of stack effects involves a linkage with a thermal network. Radioactive materials were dealt with using a gas concentration dispersion model in a multi-chamber.

From around 1994, the extensional development to handle water vapor as gas under the same model, to evaluate interactive effects of moisture and heat resulting from evaporative cooling, and integrate the function of the latent thermal loads and dew condensation calculation. On the other hand, initially a mode changing method had defined a mode number over the entire model. In a multi-room building, we installed electric heaters with thermal storage in each room. The entire model mode, however, encounters a problem in that the number of modes increases significantly if fans are started and stopped individually under room-temperature feedback control. The problem has been settled by defining separate mode numbers for each of the partial sets of computational model parameters. This settlement was prompted by a request from Hokkaido Electric Power Co., Inc. for simulation program development in 1987.

The development of the first pre- and post-processing systems was started in 1988 in response to a request from the Research and Development department of Hokkaido Electric Power Co., Inc. Unfortunately, Operating Systems in those days were inadequate for developing such a system. A House Japan project undertaken in 1994 by the Ministry of International Trade and Industry, however, gave the opportunity to develop and design a full-fledged system. In the six years beginning in 1994, it was possible to develop successfully a full-fledged system .

The computational model may be used to examine various problems and issues including those with architectural energy saving strategies, thermal environment evaluations, condensation problems and air quality assessments, as well as natural ventilation utilization as shown in the Figure5. This computational model will contribute significantly to the relevant industries in the future.

CASE STUDY OF A MULTIFUNCTIONAL VENTILATION SYSTEM

We have designed a multifunctional ventilation system having supply and exhaust shafts. The multifunctional ventilation system is characterized by:

- maximal utilization of natural force of stack effects in high- and medium-rise buildings;
- reduction in cooling loads in daytime by cooling a building structure with nighttime cool air;
- reduction in ventilation power, and enhancement of ventilation efficiency; and
- Pressured removal of smoke from emergency passages when fire occurs.

NETS was used to predict the performance of this system.

MECHANISM OF THE MULTIFUNCTIONAL VENTILATION SYSTEM

This system is made up of three elements. These elements are air supply and exhaust shafts vertically penetrating a building, and air flow direction control boxes which are installed inside the ceiling plenum at the location connecting to those shafts and of the exterior wall connecting to the outside air. The elements enable natural ventilation, fabric thermal storage, and pressured smoke removal. The inlet for the air supply shaft and the outlet for the exhaust shafts are also provided with fans for mechanical ventilation along with openings for natural ventilation.

The air supply shafts play the role of supplying fresh air to floors to be ventilated without being dirtied and warmed midway through the other floors. The exhaust shafts assume the role of directly discharging air from ventilated floors to the outside without being polluted or warmed midway through the other floors. At the airflow direction control boxes connecting the air supply and exhaust shafts to each floor's ceiling plenum, the dampers inside the box are controlled to implement suitable airflow.

The cooling building fabric at nighttime resorts to stack effects and is so controlled by the air control box dampers that cool and fresh air passes through the ceiling plenum. Daytime ventilation is so controlled by these dampers that the fresh air passes through the occupied space. If the fabric cooling resorting to outside air is unavailable, the air-conditioning system can be applied to fabric thermal storage since the ceiling slabs can be cooled by relatively inexpensive nighttime electric power.

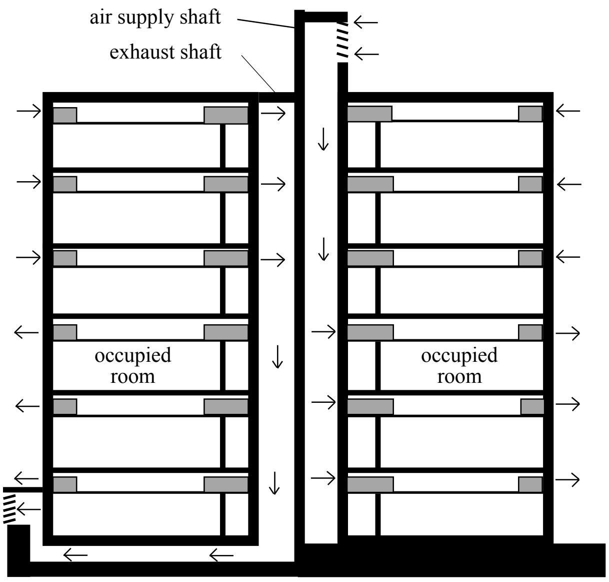

Figure6 Multi-story building section

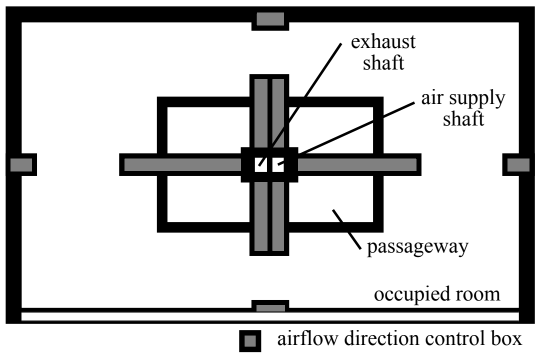

Figure7 Plan of ceiling plenum

COMPUTATIONAL MODEL AND CONDITIONS

The case study model used is a six story office building, each floor of which has an area of about 1,000 square meters. The building is outlined in Figures6 and 7. The plan of the standard floor is similar to Figure7. It has a ventilation shaft (whose sectional area is 4 square meters) at the center, a passageway (96 square meters) adjacent to the ventilation shafts, and an occupied room (900 square meters) surrounding the passageway. The full width of the southern exterior wall is composed of double-layered glass windows. The three other exterior walls are provided with no windows. The thermal network model of this building is composed of 318 nodes and the airflow network model is composed of 50 zones with 264 flow paths. Computational condiions are covered in Table2-3. As shown in Table 2, in order to compare with this multi-functional ventilation system, next two kinds of buildings were assumed. Hereupon,

--The ordinary building, the one means the usual building that does not cool the building structure by the outside air intake at nighttime.

--The mechanical storage building, the one means the building which does not make the outdoor air intake at nighttime, and whose building structure is cooled forcibly by the air conditioners.

Both operations by day were made under the same condition by keeping the room temperature 26degC.

As shown in Table 3, the calculation period was from 7 to 8 October (from 4 to 8 October, including the pre-

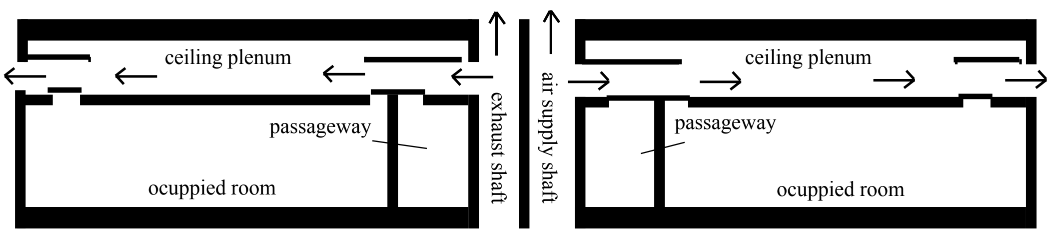

Figure8 Standard floor section showing airflow control box function

calculation period 3 days). Heat generation by the occupants, equipment and lighting per unit floor surface were given as shown in the table. As the number of occupants was determined to be 0.1person/m2, so the number of occupants per floor was 90 persons and was 540 persons for the whole building. Particularly, the heat generation by lighting was distributed as 30% for ceiling plenums, 20% for occupied rooms and 50% for floor surfaces. Moreover, during the noon recess (from 12:00 to 13:00), the heat generation value was established to 50%. The cooling equipment is operated in general during the business hours of weekdays, but in case of the mechanical storage building, the ceiling plenums should be also cooled at nighttime. Concerning the basic air conditioning time of weekdays, the pre-cooling time is from 8:00 to 9:00, the cooling time is from 9:00 to 20:00, and the temperature of occupied rooms should be regulated to be 26degC.

Figure 9 shows the meteorological conditions of the outdoor air temperature, normal direct and diffused solar radiation. The standard annual meteorological data of Tokyo by SHASEJ (The Society of Heating, Air-conditioning and Sanitary Engineers of Japan) were applied.

ENERGY SAVING EFFECTS

Figure 10 shows the temperature variation of occupied rooms and ceiling plenums, in the ordinary and in the multi-functional 6th floor of buildings. The ceiling plenum temperature of the building controlled by this system was always lower than that of the ordinary building, and the effect of building structure storage by the natural ventilation was confirmed.

Figure 11 shows the change of whole building's cooling loads with time of day. While the peak hour of cooling loads is 14:00, the peak load's reduction rate to the ordinary building is about 7.5% for the building equipped with this system, and about 20% for the mechanical building structure storage building.

Figure 12 shows the ventilation rate with the multi-functional ventilation system that means an air change rate as the amount of whole building's ventilation divided by the building's capacity.

Table4 lists data on cooling load comparisons on October 8. While the building not controlled by this system provides a daily cumulative cooling load of 7,224.23 MJ, the building controlled by this system provides a daily cumulative cooling load of 6,472.72 MJ. In other words, the latter building implements energy saving of about 10 percent. The fabric thermal storage using a mechanical cooling system raises the daily cumulative cooling load to 8,288.76 MJ, which is higher by about 15 percent than the value for the ordinary building not controlled by this multi-functional ventilation system. But this mechanical cooling system will contribute to an electric power load reduction effect of about 33 percent in daytime in terms of the cooling load.

PRESSURED SMOKE REMOVAL WHEN FIRE OCCURS

When fire occurs on a floor, the air flow direction control boxes on the floors are so controlled that outside air is applied only to the passageway on that floor through the supply shafts and the air is discharged through the air flow direction control box on the exterior wall for that floor. The air supply fan applies the maximum flow rate for pressured smoke removal. The fresh air requirement to each floor is 90[person] by 30[m3/h person] = 2700[m3/h], so the fan capacity is assumed to be 2700[m3/h] by 3[floors] = 8100[m3/h] = 2.25[m3/h]. The pressured smoke removal was simulated for three cases in which fire occurred on the first, fourth and sixth floors. The positive direction of the differential pressure through the door is defined from passageway to occupied room.

Figure13 shows the variations in differential pressure at the upper, middle and lower portions of the door on the first floor.

Figure 14 shows the differential pressure at the upper portion of the door on 1-st, 4-th and 6-th floors respectively. If the upper portion of the door is good concerning the differential pressure and the direction, the lower portion of the door should be also good.

The simulation indicates that, although the differential pressure becomes lowest at the upper portion of the door on the first floor, the differential pressure on the passageway for the room where fire has occurred is kept positive while the fire lasts. This means that air supply under the maximum fan capacity enables pressured smoke removal.

CONCLUSION

On the basis of this thermal network model with underlying state-space system theory, the three theories of predictive calculation, system identification and optimum control have been developed. This thermal network formulation will provide a platform among spatially discrete models for a diffusion system, and will facilitate the application of mathematical solutions such as system theory. Additionally, the thermal and airflow network model realized a simulation program NETS with a high degree of modeling freedom and universal applicability as a research and development tool. The case study using NETS was shown on the multifunctional ventilation system that takes advantage of stack effects produced in a multi-story building. Thus, the thermal and airflow network model is well adapted to investigate the passive and low energy architecture using natural energy.

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NOMENCLATURE

n :state dependent(unknown) nodes

n_o :state independent(given) nodes

n_g :flux sources

x_i :state(e.g.temperature) of node i

$m_{i,j}$:generalized capacitance

$c_{i,j}$:generalized conductance

$r_{i,j}$:flux input ratio(e.g.absorptance)

g_i :flux(e.g.heat flow) by source i

$\mathbf{x}={}^t(x_1, x_2, \ldots, x_n)$:state vector

$\mathbf{x}_o={}^t(x_{n+1}, \ldots, x_{n+no})$:state input vector

$\mathbf{g}={}^t(g_1, g_2, \ldots g_{ng})$:flux input vector

$\mathbf{M}$:capacitance matrix constituted of $m_{i,j}$

$[\mathbf{C}, \mathbf{C}_o]$:conductance matrix constituted of $c_{i,j}$

$\mathbf{R}$:flux input matrix constituted of $r_{i,j}$

α_i :eigenvalue of system matrix $\mathbf{M}^{-1} \cdot \mathbf{C}$

$\mathbf{P}_i$:projection operator associated with α_i

$\mathbf{f}^*$:driving vector defined as $\mathbf{M}^{-1} \cdot (\mathbf{C}_o \cdot \mathbf{x}_o + \mathbf{R} \cdot \mathbf{g})$ Details in doctorate thesis by H.Okuyama

$\mathbf{r}$:targets for state control ,see details in [13]

$\mathbf{W}_\mathbf{x}$:weighting matrix for deviation of state vector quadratic term

$\mathbf{u}_c$:control vector

$\mathbf{d}$:reference vector for control operational vector

$\mathbf{W}_c$:weighting matrix for control operational vector quadratic term

$\mathbf{e}$:observational equation error vector defined by $\mathbf{e} = \mathbf{y} - \mathbf{Z} \cdot \mathbf{a}$ See details in [8]

$\mathbf{W}$:weighting matrix for generalized least squares

T :measurement period

Table2 Compared buildings and operations

	8:00-20:00	another
building with	occupied room referece	building condition
multi functional ventilation		natural fabric cooling
ordinary building	26 degC	no ventilation
mechanical ventilation		mechanical storage

Table3 Conditions of calculation

simulation period		10/7-10/8(pre-caluculation periond 3days)	
occupants		0.1person/m^2	heat gen when fire occurs
Heat generation	occupants	70W/person	
	equipment	17W/m^2	14:00-14:02
	lighting	23W/m^2	150kW
		30% ceiling	14:02-14:04
		20% occupied room	1650kW
		50% floor surface	14:04-14:30
fresh air		3m^3/m^{2}h	3000kW
cooling schedule	storaging	20:00-8:00	
		objective point at ceiling plenum is 23degC when mechanical storaging	
	pre-cooling	8:00-9:00	
		no fresh air and no heat gen	
	cooling	9:00-20:00	
		heat gen is reduced 50% during 12:00-13:00	

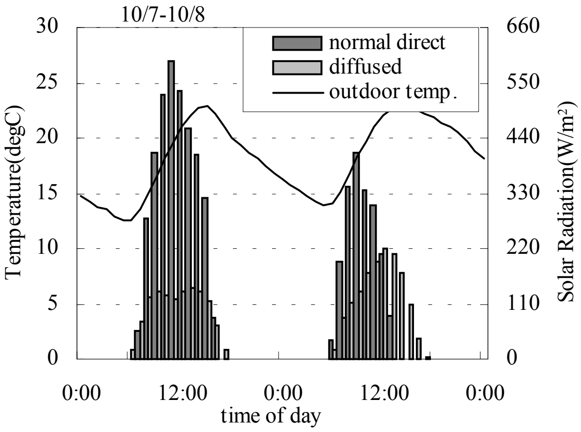

Figure9 Meteorological conditions

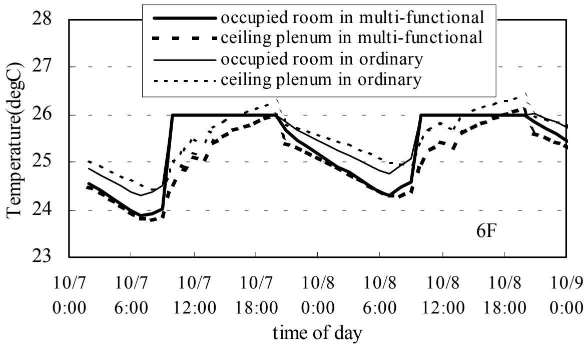

Figure10 Temperature variation

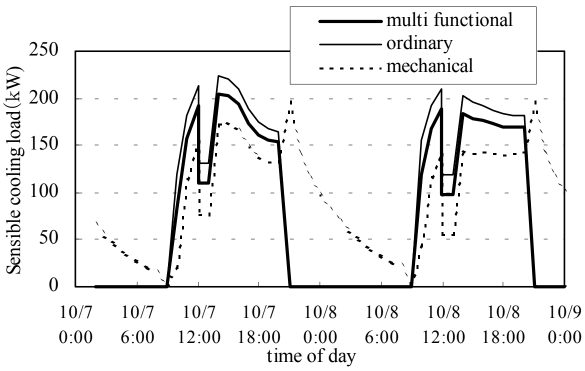

Figure11 Cooling loads variation

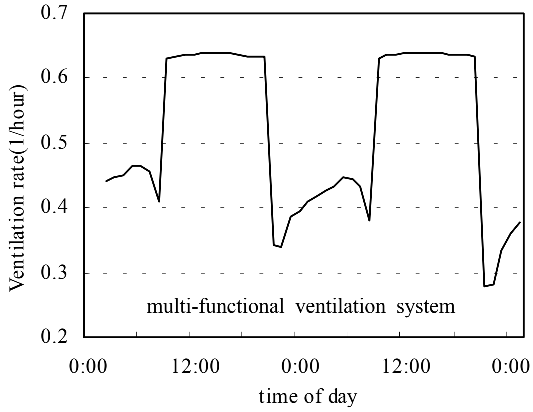

Figure12 Ventilation rate variation

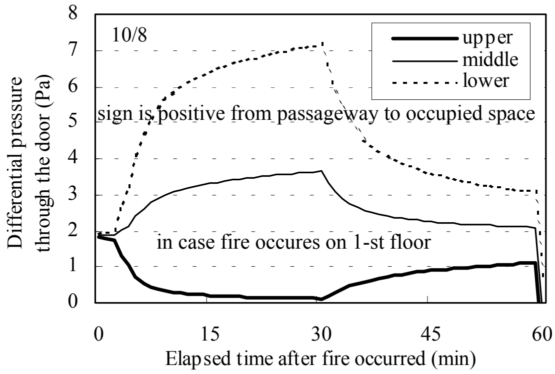

Figure13 Differential Pressure(DP) through the door on 1-st floor

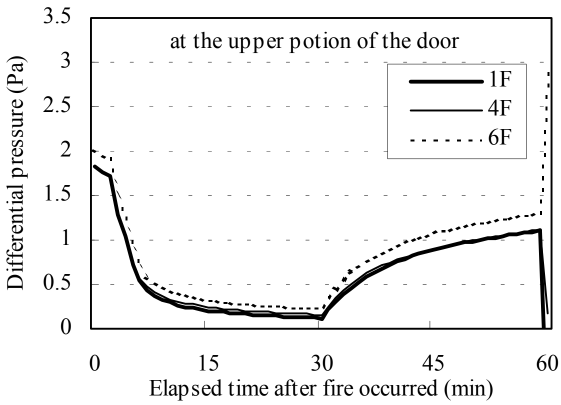

Figure14 DP at the upper portion of the door on 1-st,4-th,and 6-th floors

Table4 Comparison of each floor's cooling load (MJ)

	multi functional	ordinary building	mechanical thermal storage	
	daytime	daytime	daytime	nighttime
1F	1009.41	1145.60	895.79	604.02
2F	1024.72	1229.26	818.85	580.94
3F	1073.70	1227.47	798.22	580.88
4F	1104.45	1191.70	770.90	602.98
5F	1163.57	1231.97	808.35	603.80
6F	1096.87	1198.21	793.66	430.37
subtotal	6472.72	7224.23	4885.77	3402.99
total	6472.72	7224.23	8288.76	