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SIMULATION ON TEMPERATURE AND FLOW FIELD IN THE ATRIUM (PART1. COMPUTATION OF SOLAR RADIATION, RADIATIVE HEAT TRANSFER, AIR FLOW, AND TEMPERATURE)

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ABSTRACT

In the effective control of indoor climate in the atrium, it is very important to predict the temperature and flow fields at a design step. One of the methods for the prediction is numerical simulation. We have developed the numerical simulation system, which consists of three-subsystems as followings;

(1) the simulation system of the direct solar radiation, the diffused solar radiation and the diffused reflection of the solar radiation,
(2) the simulation system of the radiative heat transfer,
(3) the simulation system of the temperature and flow distribution which is based on the k - ε model of turbulence solved by GSMAC3D-FEM[1,2].

In this paper (Part 1), we will describe the numerical methods in which the radiation field and the convection field are solved simultaneously, and the techniques for computation of above three sub-systems. In the second paper (Part 2), the accuracy and reliability of those systems are confirmed by comparison between the numerical results and measurements, and applications for the actual design of atrium will appear[3~5].

KEYWORDS Thermal environment, Solar radiation, Radiation, Convection, Coupled analysis

1 INTRODUCTION

In recent years, the large space with the glass roof in the building, so called atrium, has been popular. But it is difficult to predict the thermal environment in the atrium at the design step since the thermal environment gets much effect from the solar radiation. Moreover, because the scale of the atrium is large, the three dimensional distribution of temperature and air velocity must be considered for the control of the environment. Therefore the three dimensional calculation is required for the analysis of the detailed distribution.

In this paper (part 1), the numerical methods for the calculation of solar radiation, radiative heat transfer, and flow and temperature field are going to be mentioned. The calculation of solar radiation gives the solar radiation absorbed as the boundary conditions for the analysis of flow and temperature field, and the solar radiation absorbed is considered amount of the direct solar radiation, the diffused solar radiation, and the diffused reflection of the solar radiation. In the analysis of the flow and temperature distribution based on the results from the solar radiation absorbed, two methods are adopted as followings;

(1) First the radiation field is solved, and next the convection field is solved (method 1).

(2) The radiation and the convection field are solved simultaneously (method 2).

By the calculation of the radiative heat transfer, amount of radiative heat transfer among boundaries can be obtained. The temperature and flow velocity in the atrium is solved by the GSMAC3D finite element method using the k - ε model of turbulence as the basic equations.

An advantage of this system is in the calculation based on the finite element method. Therefore the solar radiation, the radiative heat transfer, and the temperature and flow field calculation can be applied for the atrium having geometrically complicated indoor spaces.

2 OUTLINE OF THE THERMAL ENVIRONMENT ANALYSIS SYSTEM

This simulation system is based on the finite element method(FEM). The FEM has a big advantage in case of computation of geometrically complicated domain. Therefore, this system can be applied for the calculation about solar radiation, radiative heat transfer, flow and temperature field in a complex-shaped domain very easily. The calculation procedure is expressed in Fig.1. However, this system is restricted to the stationary analysis.

3 COMPUTATION OF THE SOLAR RADIATION ABSORBED

The direct solar radiation, the diffused solar radiation, and the diffused reflection on boundary elements are required in the calculation of the absorbed heat quantity. Here, the boundary element is the boundary of the finite element mesh. In case of the hexahedral element mesh, the boundary element is quadrate (Fig.2). The details of numerical computation are reported in reference [3,4].

4 COMPUTATION OF THE RADIATIVE HEAT TRANSFER

To calculate amount of the radiative heat transfer on boundary elements, computation of the view factor must be considered first. The view factors depend upon the relative locations among all boundary elements. Number of pair boundary element is very large. Therefore, computation efficiency is required to be higher for saving the computation time[4]. View factor F_{12} from boundary element A_1 to A_2 is defined by equation (1);

$$F_{12} = \frac{1}{\pi A_1} \int_{A_1}\int_{A_2} \frac{\cos\theta_1 \cos\theta_2}{r^2} dA_1 dA_2 \tag{1}$$

Since equation (1) can not be integrated analytically, it is needed to be numerically. Therefore, we approximate equation (1) to equation (2);

$$F_{12} \sim \frac{1}{\pi A_1} \sum_{i=1}^{n_1} \sum_{j=1}^{n_2} \frac{(R_{ij}\cdot N_1)\cdot(-R_{ij}\cdot N_2)}{|R_{ij}|^4} dA_i^1 dA_j^2 \tag{2}$$

where $R_{ij} = P_j^2 - P_i^1$, P_i^1, P_j^2 are centroid of divided small element dA_i^1, dA_j^2, N_1, N_2 are unit normal vector of boundary element A_1, A_2, n_1, n_2 are partition number of boundary element A_1, A_2, respectively (Fig.3). Partition number n_1, n_2 of boundary element are defined by its size,shape, position (Table 1). When r is to be zero, $1/r^2$ is to be singularity. To overcome this problem, the partition number, n_1, n_2 are increased automatically.

Model of radiative heat transfer on boundary element is shown in Table 2. Here temperature, irradiation and radiosity in each boundary element are constant. Convective heat transport is simply modeled in terms of $\alpha_{ci}(T_{in}-T_i)$. T_{in}(constant), T_i are independently solved by equation (6) without computation of convection field (method 1). Equation (3)~(6) are solved by iterative method explicitly (SOR) to make the computation faster.

5 COMPUTATION OF TEMPERATURE AND FLOW DISTRIBUTION

In computation of flow and temperature field, non-isothermal k - ε model of turbulence is used as basic equations shown in Table 3. Momentum equation is described in rotational form. These equations in Table 3 are discretized by Galerkin weight residual formulation with hexahedral elements and solved by the GSMAC3D code. Boundary conditions are shown in Table 4. Boundary conditions on walls are approximated by the generalized log-law and the wall function method. The details of discretization and numerical computation are reported in reference [1,2].

6 COUPLING METHOD OF RADIATION AND CONVECTION

6-1 TRANSFER THE RADIATION FIELD TO THE CONVECTION FIELD

Transfer the radiation field to the convection field is carried out by heat quantity Q_i (= J_i - G_i + I_i) which is the heat flux from boundary element to air, and which is computed in the radiation field. Thermal equilibrium equation (7) is assumed in temperature field (Fig.4);

$$q_2 = q_1 + Q_i, \quad q_2 = K' \ (T_i - T_{ref}), \quad q_1 = \alpha_{ci} \ (T_o - T_i) \tag{7}$$

Calculating q_1 from K', Tref, Qi and To in previous step, the boundary condition is given by substituting q_1 for the boundary integration term of the convective diffusion equation for temperature. If q_1 is fixed, it is to be substituted directly for the boundary integration term. In case of the adiabatic wall, q_1 is to be zero. As a result, the convection field is independently solved.

6-2 TRANSFER THE CONVECTION FIELD TO THE RADIATION FIELD

Transfer the convection field to the radiation field is carried out by air temperature Tin in flow and temperature computation. Tin is referred the centroid temperature of the nearest mesh to the boundary (Fig.4). In the radiation field, equation (6) used in method 1 is not necessary because Tin is known in method 2. The algorithm of method 1 and method 2 is shown in Fig. 5 .

7 CONCLUSION

In this paper, we describe the numerical method for computation of temperature and flow distribution in the atrium. In this method, at first solar radiation field is solved, and then the radiation field and the convection field are solved simultaneously. Coupled computation of the radiation field and the convection field makes it possible to get much more accurate results than conventional methods.

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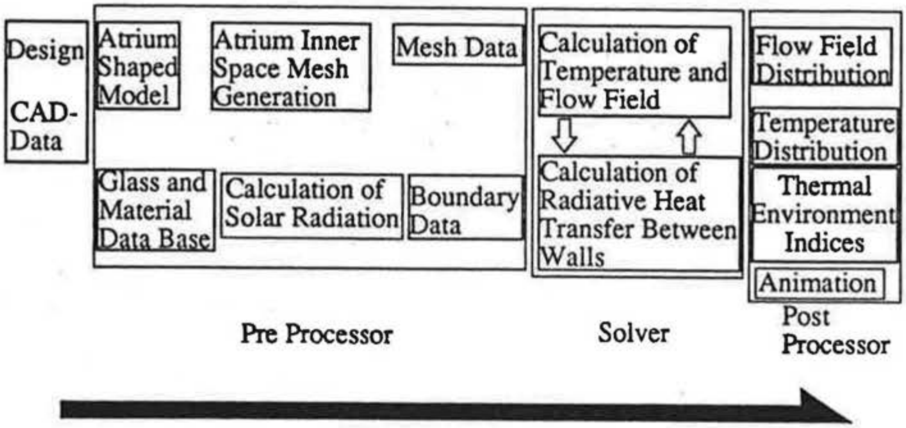

Fig.1. Numerical analysis on thermal environment.

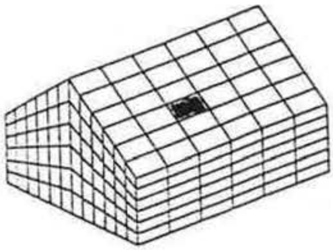

Fig. 2. Boundary element

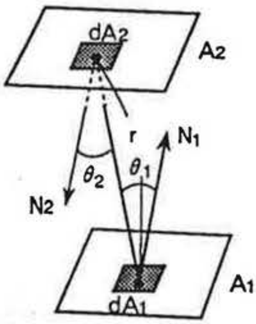

Fig.3a. View factor F_{12}

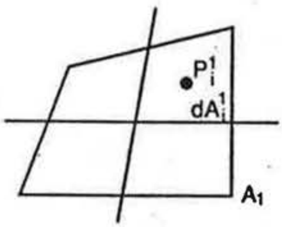

Fig. 3b. Partition of element A_1 ($n_1 = 4$)

Table 1 Equation for calculating number of partitions of n_1, n_2

Aspect partition ratio of an element

$$= \begin{cases} k_a : k_a A & (A < 4), \\ k_b : k_b A & (A \geq 4) \end{cases}$$

$$k_a = \begin{cases} 2 & (p \geq 0), \\ 4 & (p < 0) \end{cases} \quad k_b = k_a \ / \ 2,$$

$$p = r - k_p \max(A_1^{1/2} A_2^{1/2}),$$

Table 2 Basic equations of radiation field

Heat balance on boundary element

$$\underbrace{\alpha_{ci}(T_{in} - T_i)}_{\text{convective heat transport}} + \underbrace{J_i - G_i}_{\text{radiative heat transfer}} + \underbrace{I_i}_{\text{solar radiation absorbed}} = \underbrace{K'(T_i - T_{ref})}_{\text{heat penetration}}, \quad (3)$$

$$J_i = \sum_{j=1}^{N} F_{ij} G_j, \quad (4)$$

$$G_i = \sigma \varepsilon T_i^4 + (1-\varepsilon) J_i, \quad (5)$$

Heat balance in analysis space

$$\int_{\Gamma} \alpha_{ci} (T_i - T_{in}) d\Gamma = Q. \quad (6)$$

(notation)

(Table 1)

A : aspect ratio of element, r : distance between the center of elements, A_1,A_2 : each element area, k_p : constant.

(Table 2)

J_i : irradiation of boundary element, G_i : radiosity, T_i : surface temperature, T_{in}: room air temperature, F_{ij} : view factor from boundary element i to boundary element j, I_i : solar radiation absorbed, σ : Stefan-Boltzmann's constant, ε : emissivity, α_{ci} : the coefficient of convective heat transfer, K' : over-all heat transfer coefficient without contribution from inner total heat transfer, T_{out} : outer side reference temperature, Γ : boundary of domain, Q : heat source or sink caused by air conditioner or ventilation, N : a number of elements consisting closed space.

Table3 Basic Equations (k-ε model of turbulence)

$$\frac{\partial U_i}{\partial x_i}=0$$

$$\frac{\partial U_i}{\partial t}=-\frac{\partial}{\partial x_i}(P+\frac{2}{3}k+\frac{1}{2}U_kU_k)+\varepsilon_{ijk}U_j\omega_k+\frac{\partial}{\partial x_j}\{(\frac{1}{Re}+\nu_t)(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i})\}+A_rT\delta_{i3}$$

$$\frac{\partial k}{\partial t}+U_j\frac{\partial k}{\partial x_j}=\frac{\partial}{\partial x_j}(\frac{\nu_t}{\sigma_k}\frac{\partial k}{\partial x_j})+(P_k+G_k)-\varepsilon$$

$$\frac{\partial \varepsilon}{\partial t}+U_j\frac{\partial \varepsilon}{\partial x_j}=\frac{\partial}{\partial x_j}(\frac{\nu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_j})+\frac{\varepsilon}{k}(C_1P_k+C_3G_k)-C_2\frac{\varepsilon^2}{k}$$

$$\frac{\partial T}{\partial t}+U_j\frac{\partial T}{\partial x_j}=\frac{\partial}{\partial x_j}\{(\frac{1}{Pe}+\frac{\nu_t}{\sigma_T})\frac{\partial T}{\partial x_j}\}$$

$$P_k=\nu_t(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i})\frac{\partial U_i}{\partial x_j},\quad G_k=-A_r\frac{\nu_t}{\sigma_T}\frac{\partial T}{\partial x_i}\delta_{i3}$$

$C_D=0.09$, $C_1=1.44$, $C_2=1.92$, $\sigma_k=1.0$, $\sigma_\varepsilon=1.3$, $\sigma_T=1.0$

$C_3=0$ for $G_k \le 0$

$C_3=C_1$ for $G_k > 0$

Table 4 Boundary Conditions

Supply outlet Boundary	$U_i=U_i^{in}$, $T=T^{in}$, $k=k^{in}$, $l=l^{in}$, $\varepsilon=\varepsilon^{in}=C_D\frac{(k^{in})^{3/2}}{l^{in}}$
Exhaust inlet Boundary	$U_i=U_i^{out}$ T, k, and ε are under free slip condition.
Openning boundary on a wall	$P=P_0$ $T=T_0$, $k=k_0$ and $\varepsilon=\varepsilon_0$ for inflow case. T, k, and ε are under free slip condition for outflow case. Judgement of inflow or outflow depends upon the sign of inner product of outward normal vector and air velocity vector.
Wall boundary	(Velocity field) First u^{*2} is calculated from eq (8), then the shear stress on the wall boundary is obtained. The boundary condition about velocity field is given by substituting the shear stress for the boundary integration term of the momentum equation. $\frac{U_{1t}\cdot(C_D^{1/2}k_1)^{1/2}}{u^{*2}}=\frac{1}{\kappa}\ln(\frac{E\cdot h_1\cdot(C_D^{1/2}k_1)^{1/2}}{\nu})$ (8) $U_{1n}=0$, $\frac{\partial k}{\partial n}=0$, $\varepsilon_1=\frac{C_D^{3/4}\cdot k_1^{3/2}}{\kappa\cdot h_1}$, $E=9.0$, $\kappa=0.42$ (Temperature field) refer to eq.(7).

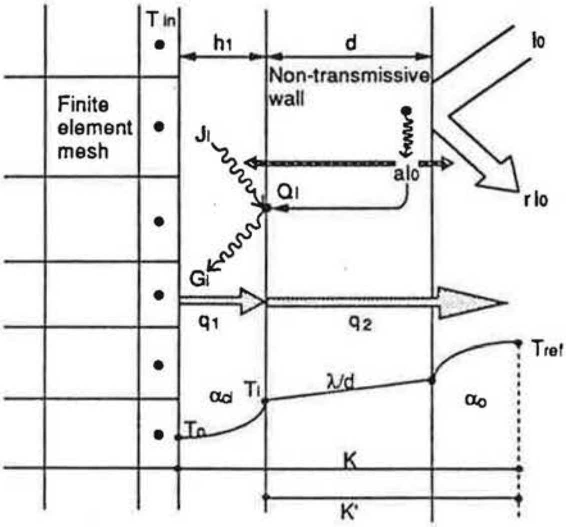

Fig.4. Heat flux on boundary conditions
(Example of non-transmissive wall)

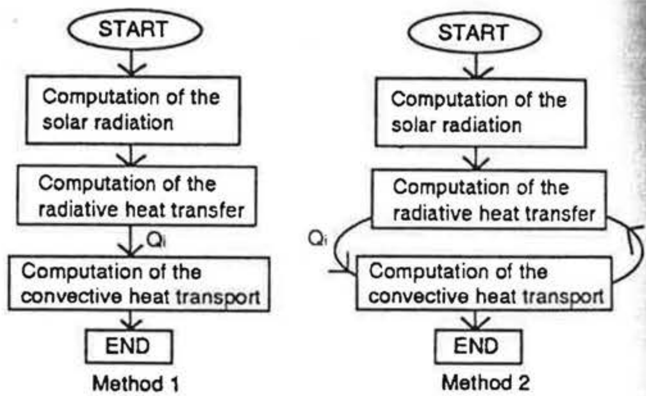

Fig.5. Algorithm of method 1 and method 2

(notation)

(Table 3)

U_i : Mean air velocity, P : Mean pressure, k : Turbulence kinetic energy, ε : Turbulence dissipation rate, T : Mean temperature, ν_t: Kinetic eddy viscosity, P_k: Production term of k, G_k : Production term of k caused by buoyancy effect, ε_{ijk}: Permutation tensor, ω_k : Vorticity vector, Re : Reynolds number $(=\frac{U_0\cdot L_0}{\nu})$, Ar : Archimedes number $(=\frac{g\beta\Delta T_0L_0}{\nu})$, Pe : Pechlet number(Re Pr), Pr : Prandtle number u, U_0 : Reference air velocity, L_0: Reference length, ν : Kinetic viscosity, g : Gravitational acceleration, ΔT_0 : Reference temperature difference, β : Thermal expansion rate of air.

(Table 4)

U_i^{in}, T^{in}, l^{in}, ε^{in} : Boundary values at supply outlet , U_i^{out} : Boundary values at exhaust inlet, l : Length scale of turbulence, P_0 : Pressure at openning boundary on the wall, T_0 , k_0 , ε_0 : Boundary values at openning boundary on the wall, u* : Friction velocity $(=\sqrt{\frac{\tau_w}{\rho}})$, τ_w : shear stress on the wall boundary, ρ : Density of air, U_{1t} , U_{1n} : Tangential and normal velocity on the wall boundary, k_1 , ε_1 : k and ε values on wall boundary, h_1 : Length from the wall surface to the boundary of the adjacent element, κ : von Karman's constant.