A STUDY ON NUMERICAL PREDICTION METHOD OF INDOOR THERMAL ENVIRONMENT INCLUDING HUMAN BODY

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ABSTRACT

In the evaluation of thermal environment in a living quarter, thermal sensation index can be obtained from heat balance in occupants. In particular, however, in personal air-conditioning or in task-ambient air-conditioning, it is necessary to perform more detailed prediction and evaluation of air flow and air temperature distribution around human bodies. For this purpose, indoor environment including bodies of the occupants must be estimated and evaluated, and experiments using thermal mannequin or human subjects and numerical prediction such as CFD are useful.

The primary aim of the present study was to establish a method to obtain air flow and air temperature distribution by numerical prediction method. Major features of the prediction method are as follows:

- Air flow and air temperature distribution around bodies of the occupants is obtained by CFD. The κ - ε two equation turbulence model commonly used as turbulence model is adopted. To cope with the complicated configuration of human bodies, generalized curvilinear coordinate system is used. As the calculation method, SIMPLE method and SIMPLER method are adopted. On continuity equation residual, calculation time, calculation stability, etc., the two methods are compared with each other.
- Complicated configuration of human body in seated position is approximated by measurement of coordinates of a subject. The surface is approximated using triangles.
- Calculation relating to giving and receiving of radiation heat and to heat balance inside the human body is not performed. To facilitate the calculation of heat radiation condition of the surrounding walls and human bodies, it is assumed that surface temperature is already known.
- As a case study, thermal and air environment around occupants in a room is estimated when floor panel heating is installed in a small experimental room.

1. INTRODUCTION

In the evaluation of thermal environment in a living quarter, thermal sensation index can be obtained from heat balance in occupants as a whole [1]. In particular, however, in personal air-conditioning or in task-ambient air-conditioning, it is necessary to perform more detailed prediction and evaluation of air flow and air temperature distribution around human bodies. For this purpose, indoor environment including bodies of the occupants must be estimated and evaluated, and experiments using thermal mannequin or human subjects and numerical prediction such as CFD are useful.

In the numerical prediction, it is necessary to use an adequate method to calculate the data such as heat balance model inside the bodies of the occupants, receiving and giving of radiation heat on body surface and wall surface, preparation of a model in shape of human body, and air temperature and air flow distribution around human bodies.

(1) As a model of heat balance inside human body, a model used in PMV [2] may be the simplest [3]. Next follow 2-node model of SET* [4], 6-part model of Stolwijk and Hardy [5], 16-part model of Tanabe et al. [6], etc. To match the detailed air flow calculation by CFD, it is desirable to use a model, which can be handled by dividing a human body to head, trunk, limbs, etc.

(2) To calculate giving and receiving of radiation heat between bodies of occupants and wall, there is a method to obtain shape factor by Monte Carlo method through approximation of human body configuration using rectangular parallelepipeds [3]. For the complicated human body configuration, calculation method is also proposed on shape factor, and it is not impossible to calculate.

(3) Micrometeorology around occupants' bodies can be calculated by CFD. At the same time, convection heat transmission on occupants' bodies and wall can be calculated by CFD. Murakami et al. [7] reproduced a human body in standing position using low-Reynolds-number κ - ε turbulence model with based on

generalized curvilinear coordinate system and performed detailed assessment. Because it is necessary to perform very fine cell division, both calculation time and storage capacity may be considerably increased.

In the present study, as a part of a study to establish a method to calculate air flow and air temperature distribution around occupants' bodies through numerical prediction method by combining (1) - (3) above, it is attempted to assess the method to calculate air flow described in (3) above. As for (1) and (2), calculation is simplified by giving adequate values to temperature of the surrounding wall surface and human body surface. Because calculation may become unstable when solving the model of heat balance inside the human body, it is important to have stability in calculation of CFD on natural convection around human body. In the present study, SIMPLE method and SIMPLER method [8] are compared with each other in a field of natural convection caused by floor panel heating when there is an occupant's body in a room.

2. CALCULATION METHOD

2.1 Turbulence Model and Finite Difference Scheme

In the present study, κ - ε two equation turbulence model of Viollet type was adopted, taking the effect of buoyancy into consideration. QUICK scheme was used in convective term of velocity equation, upwind differencing was used for κ, ε and air temperature θ, and central difference was used for the others. For further details such as basic equations, refer to the literature [9].

2.2 Coordinate System

By generalized curvilinear system based on regular grid system, grid is set around complicated human body configuration. To generate the grid, measurement was made on a male subject with physical height of 1.63 m and body weight of 55 kg when he was sitting on a chair, and all operations were performed manually. The metrics required for the calculation were obtained from coordinate values by central difference.

2.3 Velocity Equation and SIMPLE Method

Generalized curvilinear system (x, y, z) is converted to orthogonal coordinate system (ξ, η, ζ) and contravariant velocity components Ue to Wd of cell interface are used, and continuity equation is turned to the equation (1). If transport equation of velocity component u at cell center is discretized, it can be written as the equation (2). Because the values of v and w can be obtained in similar manner, simultaneous linear equations of these values are solved at first, and provisional values of u*, v*, and w* are obtained. Contravariant velocity components U, V, and W at the cell center are obtained by the chain rule. By synthesizing these values, contravariant component Ue of cell interface is obtained from the equation (3). In this case, by adopting deformation of Rhie and Chou [10], approximation is performed using pressure gradient between two adjacent points. The values Uw to Wd are obtained in the same manner and are substituted in the equation (1), and chaining equation between pressure and velocity can be obtained. Then, discretization equation relating to the corrected pressure value is solved, and the values u to w and Ue to Wd are corrected using pressure and the equations (2) and (3). The transport equation of κ, ε and θ is turned to a discretization equation similar to the equation (2), and the equations can be sequentially solved.

$$(1)\ (Ue - Uw)d\eta d\zeta + (Vn - Vs)d\xi d\zeta + (Wu - Wd)d\xi d\eta$$

$$(2)\ f \cdot u = \sum f_{nb} \cdot u_{nb} - (\xi_x \pi_\xi + \eta_x \pi_\eta + \zeta_x \pi_\zeta) + f_c$$

$$(3)\ Ue = \frac{U + U_{i+1}}{2} - \{A(\pi_{i-1} - \pi_{i+1}) + A_{i+1}(\pi - \pi_{i+2})\} + \overline{A}(\pi - \pi_{i+1})$$

2.4 SIMPLER Method

In the SIMPLER method, provisional calculated velocity u^+ is explicitly obtained using the equation (4). Similarly, the values of v^+ and w^+ are obtained, and provisional contravariant velocity components U^+, V^+ and W^+ of the cell center are found. The values such as Ue^+ of cell interface are obtained from the equation (5) instead of the equation (3), and by substituting these values to the equation (1), discretization equation of pressure can be obtained. Pressure is found by solving this equation, and contravariant velocity Ue of the cell interface is corrected using the equation (6) and the like. Then, the coefficients fnb and fc in the equation (2) are re-calculated (*1), and velocity components u, v and w are solved. The subsequent procedure is the same as in the SIMPLE method.

(4) $\hat{u} = \frac{1}{f}\left\{\sum f_{nb} \cdot u_{nb} - \left(\xi_x \pi_\xi + \eta_x \pi_\eta + \zeta_x \pi_\zeta\right) + f_c\right\}$

(5) $\hat{Ue} = \frac{\hat{U} + \hat{U}_{i+1}}{2} - \left\{A\left(\pi_{i-1} - \pi_{i+1}\right) + A_{i+1}\left(\pi - \pi_{i+2}\right)\right\}$

(6) $Ue = \hat{Ue} + \bar{A}\left(\pi - \pi_{i+1}\right)$

Flow charts of these two methods are shown in Fig. 1. As the solver of the simultaneous linear equations in the present study, line-by-line method with TDMA was used. The adopted relaxation factor was 0.8 for pressure only, and 0.5 for others.

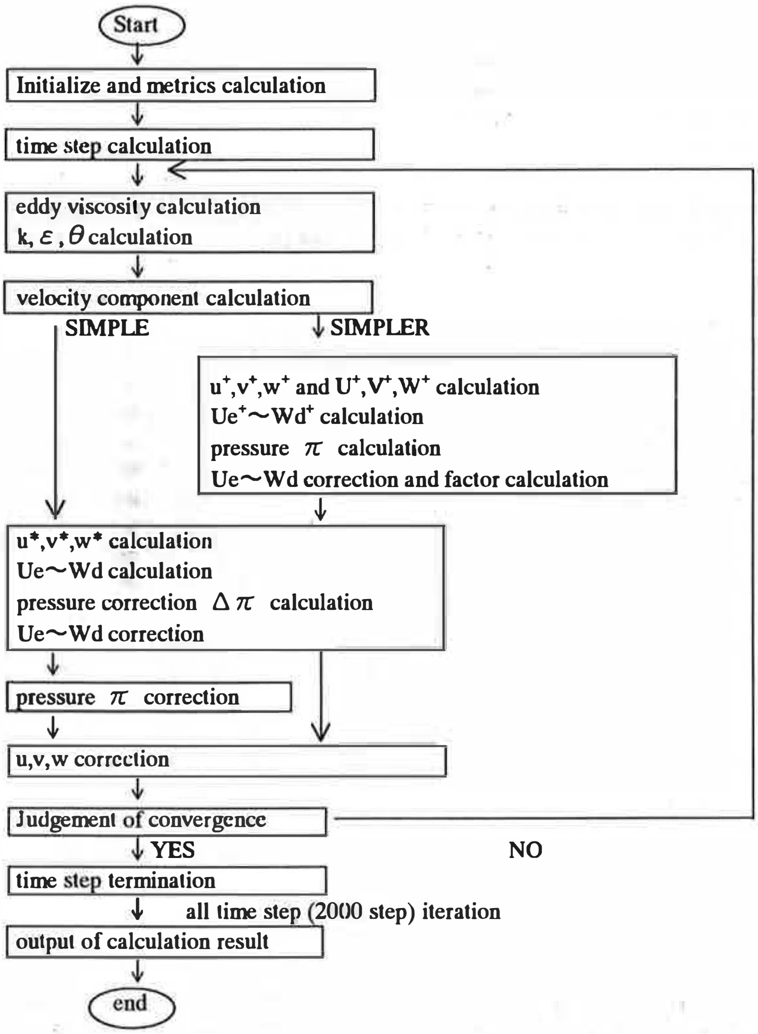


Fig.1 Flow chart of SIMPLE and SIMPLER method

3. CONDITIONS FOR CALCULATION

3.1 Room to be calculated

It is assumed that there is a human body sitting on a chair at the center of a small experimental room as shown in Fig. 2. In the calculation, no consideration was given on the chair. In a coordinate setting that is symmetrical with respect to x-axis, calculation was performed only for one side in the room using symmetrical condition. It was assumed that one side of a cell was about 100 mm in length, and it was divided to cells: 21 × 43 × 22 = 19866 cells.

3.2 Setting Conditions

It was assumed that the entire floor was heated, and that floor surface temperature was at 30℃ and the other wall surface was at 20℃. Under the conditions that metabolic rate was 1 Met, clothing thermal resistance 1 clo, humidity 50%, room air temperature 22℃, and MRT 23℃, PMV calculation was performed. It was assumed that head and hands without clothing were at 34℃ and surface temperature of the clothing on human bodies was 28℃ shown in Fig. 3.

Room height of 2.26 m was used as reference length. Using reference temperature of 20℃, reference temperature difference of 10℃, and buoyancy velocity, reference velocity was calculated as 0.864 m/s.

Reynolds number = 1.3×10^5

Grashoff number = 1.7×10^{10}

Archimedes number = 1.0

The calculation in the present study is turned to dimensionless because of these reference values. With time differencing interval of Δt = 1.0 (approx. 2.6 seconds), calculation was performed up to 2000 steps (after about 5200 seconds).

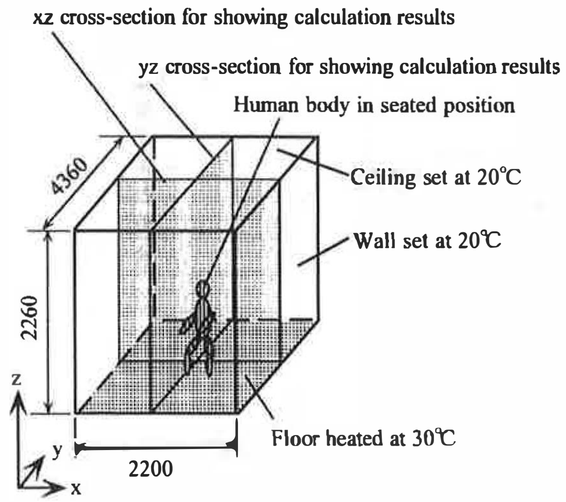


Fig.2 Room to be calculated

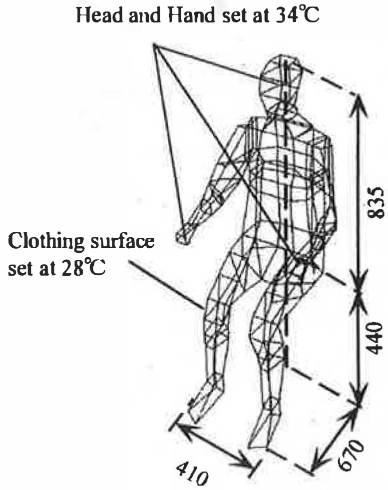


Fig.3 Setting conditions for human body

4. CALCULATION RESULTS

4.1 Results of Air Temperature and Air Flow Distribution

Fig. 4 shows air flow vector and air temperature distribution on xz-centered cross-section and yz-centered cross-section by SIMPLER method. Isothermal lines are drawn at every 0.1℃, and air temperature distribution is low in the room as a whole. Air temperature is high near human bodies, and in particular, near head of the occupant with high preset temperature values. This gives influence on air flow vector, which tends to increase along the surface of human body. Air flow velocity is about 0.2 m/s above the head. This shows air flow distribution near complicated configuration of an occupant sitting on chair in the room. Calculated solution by SIMPLE method gives similar results.

4.2 Transition of Kinetic Energy

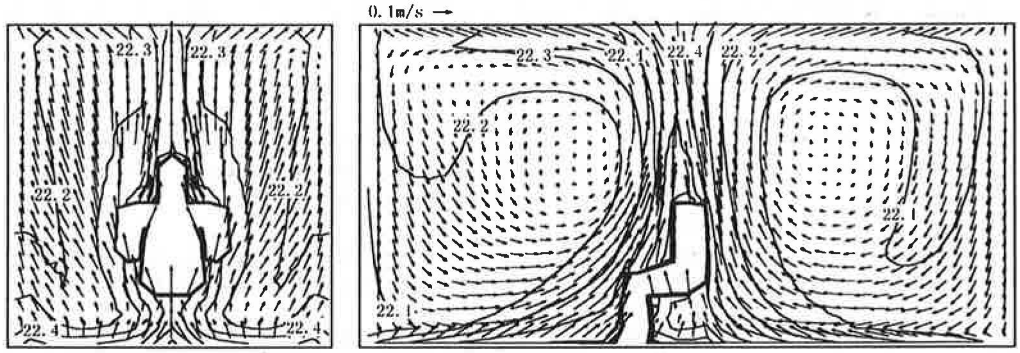
Fig. 5 shows transition of average kinetic energy at cell center velocity in the 2000 step calculation.

Because this is the calculation of natural convection, no conspicuous energy change is observed in the early stage of calculation. Energy is gradually increased, but it appears that steady state can be reached earlier when SIMPLE method is used. In both methods, steady state seems to be reached at about 2000 steps.

4.3 Continuity Equation Residual and Calculation Stability

Fig. 6 shows transition of standard deviation of continuity equation residual for all cells. Convergence in each time step is assessed by this, and convergence decision constant is 1.0×10^{-6}. Almost no decrease is noted after 300 steps in SIMPLE method, while, in SIMPLER method, the decrease gradually begins at about 1200 steps although it is accompanied with vibration. The decrease of residual is more remarkable in SIMPLER method, and it is certain that the calculation satisfies the continuity equation well.

The number of iterations of inner loop in each time step is generally lower in SIMPLER method, and there is a tendency to decrease according to time step and convergence in one time step is earlier. SIMPLER method is more stable. However, calculation in one time step is higher in SIMPLER method, and it seems that it does not contribute much to the reduction of calculation time. In the two methods, calculation time is approximately equal to each other in 2000 steps (*2).



(a) xz cross-section (b) yz cross-section

Fig.4 Air flow vector and air temperature distribution of calculation results (SIMPLER)

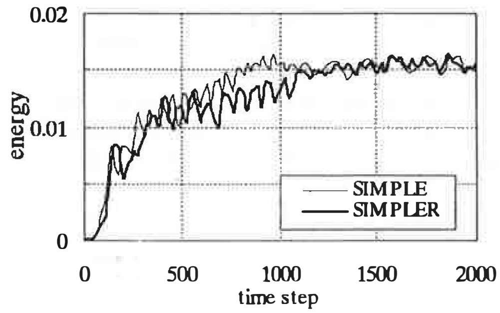


Fig.5 Transition of kinetic energy

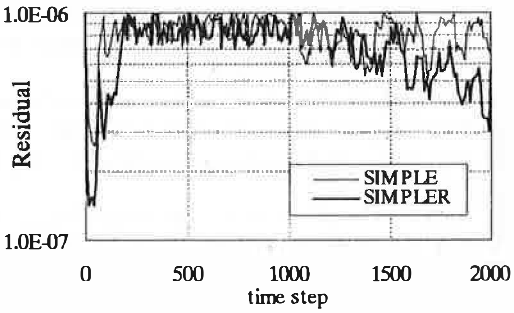


Fig.6 S.D. of continuity equation residual

5. CONCLUSION

In the present study, the author established a numerical method for calculating 3-dimensional non-isothermal turbulence flow based on generalized curvilinear coordinate system, using SIMPLE and SIMPLER methods. As a result, it was confirmed that SIMPLER method satisfies continuity equation better and it is more stable as calculation method. It is expected that this will be an effective method when combined with heat balance model inside human body and calculation of giving and receiving of radiation heat to and from the surrounding walls.

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NOTES

(*1) In orthogonal coordinate system, the re-substitution of the factors has no meaning in SIMPLER method based on staggered grid. When based on regular grid, re-substitution gives no remarkable advantage. Because the factors of u, v and w are calculated twice, the calculation time becomes a little longer. In the calculation based on generalized curvilinear coordinate system, SIMPLER method provides no advantage compared with SIMPLE method unless re-substitution is performed. The transition of residual is almost the same as in SIMPLE method, and steady state is not reached at 2000 steps.

(*2) The calculation in the present study was executed using personal computer with CPU of DEC Alpha 21064A/275 MHz. Calculation time was about 8 hours at 2000 steps. This approximately equals to the calculation time (7.5 hours) found in the literature, i.e. a study based on orthogonal coordinate system, including calculation of giving and receiving of radiation heat, and having a great number of cells (65790 cells).

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