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Numerical Study on an Atrium by Means of Macroscopic Model and k-ε Turbulence Model

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ABSTRACT

In designing air-conditioning systems for large-scale indoor spaces, it is important to predict the air velocity and temperature distributions in such spaces to enable indoor climate to be controlled effectively. The indoor climate can be predicted by two numerical simulation methods: one is a rough study by using a macroscopic model and the other is numerical simulation based on a turbulence model. Each method has its own limitations. For instance, the former method cannot provide the detail data of the flow and temperature fields whereas the latter method has a drawback in that it is difficult to determine proper boundary conditions concerned with heat transfer at wall surfaces for the numerical simulation study. This paper describes the results of studies on indoor climate of a large-scale space by these two methods, and presents that the problems involved can be solved by the combined use of two methods.

KEYWORDS

Macroscopic Model, k-ε Turbulence Model, Large-scale Indoor Climate

1. INTRODUCTION

There are two numerical simulation methods of predicting the thermal environment of large-scale indoor spaces such as atriums; namely, the "macroscopic analysis method" (hereafter referred to as "macroscopic model") and airflow simulation based on the "turbulence model" (Murakami et al. 1990). When the proper conditions are used, the calculation results of both the methods are reasonably precise and these methods are already being applied to design and analysis of thermal environment of large-scale indoor spaces.

However, details of the airflow and temperature fields cannot be examined with the results of macroscopic model simulation only. On the other hand, in the case of the turbulence model, the boundary conditions concerned with heat transfer at wall surfaces which have the most significant effect on the analysis results have often to be based on rather bold assumptions.

As illustrated in Fig. 1, this paper describes that most of the limitations inherent to each of these methods can be eliminated by making calculations using the aforesaid two methods in combination.

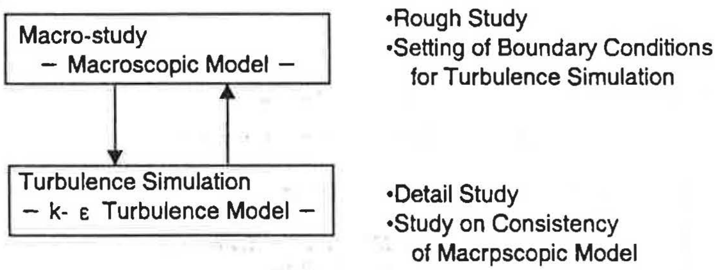


Fig. 1 Relationship between Macro-Study and Turbulence Simulation

2. STUDY BASED ON MACROSCOPIC MODEL

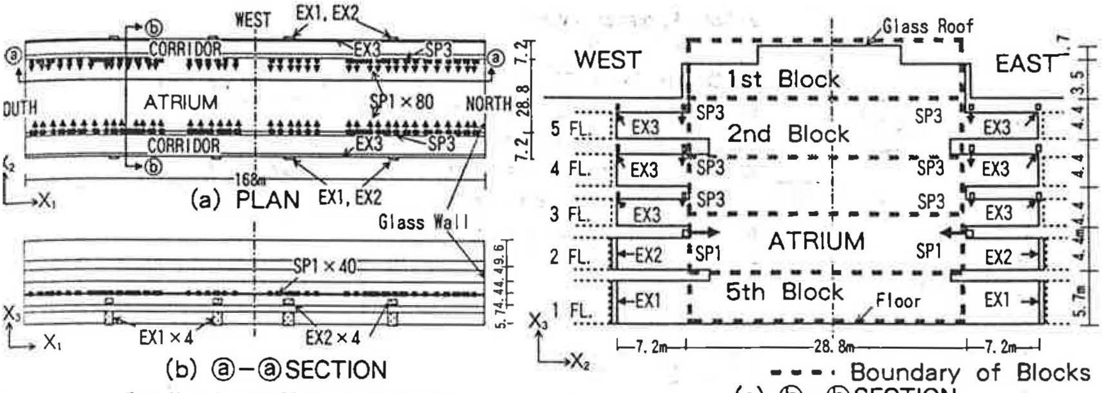
2.1 General Description of Study

Study is conducted based on Togari group's "Block Model / Wall Surface Airflow Model "(Togari et al. 1991, see Notes). Wall surface temperatures are calculated using the formula shown in Fig. 3, taking mutual radiation between wall surfaces into consideration.

Conditions for macroscopic model study are indicated in Tables. 2 and 3. The local air conditioning for the passage area for the 3rd to 5th floor and the local ventilation for the region near the ceiling are so treated as noted in Table 2. The objective of this present study is the atrium shown in Fig. 2.

2.2 Results of Macroscopic Study

As shown in Figs. 4 and 5, in Case 3 where local air conditioning is assumed for the passage areas at the 3rd to 5th floor, the temperatures of the 2nd to 4th blocks are approximately 6 to 8 ℃ lower, and the temperatures of the 1st and 5th blocks are 2 ℃ to 4 ℃ lower than in Case 1. Also, in Case 4 where the upper region of the atrium is assumed to be ventilated, the temperature in the 1st block is about 2.5℃ lower and that in all other blocks is 0.5 to 1 ℃ lower than in Case 3. It is shown



East-West Length:28.8m, South-North Length: 170.0m.
South and north walls are composed of glass. East and west walls are borderd on adjoining room.

Fig. 2 Objective of Analysis

Table 1 Conditions of Airflow at Supply and Exhaust Openings

Symbol	Type of Openings	Floor	Airflow Volume [m³/H]	Velocity at openings [m/s]	Number of Openings	Airflow temp. [℃]
SP1	supply	2F	2000	3.5	80	16.0
SP3	supply	3-5F	17000	0.7	6	16.0
EX1	exhaust	1F	16000	1.0	8	-
EX2	exhaust	2F	4000	1.0	8	-
EX3	exhaust	3-5F	17000	1.0	6	-

Table 2 Case for Macroscopic Model Study

System	Case1	Case2	Case3	Case4	Notes
Local Air-Conditioning System	OFF	OFF	ON	ON	Thermal Load at 2-4 Blocks is -116000 kW
Local Ventilation System at 1st Block	OFF	ON	OFF	ON	Exchange Airflow Volume is 50000 m³/H

Table 3 Analisys Conditions for Macroscopic Model Study (at noon in summer)

(a) Value of Solar Radiation [kW/m²]

	South	North	W&E	Horizontal
Direct Radiation	207	0	0	730
Difuse Radiation	54	54	54	108

(b)Properties of Glass Wall and Roof

	Permeability	Reflectivity	Absorptivity	Notes
Glass Wall	0.65	0.06	0.29	Absorption Glass
Glass Roof	0.10	0.50	0.40	Absorption Glass with Blinds

(c)Absorpted Heat of Solar Radiation [kW/m²]

Glass Wall (South Wall)	76	Glass Roof	335
Glass Wall (North Wall)	16	Floor	103
East Wall and West Wall	16	Inner Wall	17

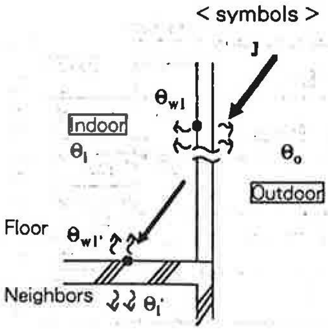
(d)Others

Block no		Height [m]	Supply [m³/H]	Exhaust [m³/H]	α_i *2) [kW/m²]	K_i *3) [kW/m²]	Ref. Temp. [℃]
1	Roof	6.7	—	—	3.5	11.6	Outdoor Temp. 32℃
	Wall		50000	50000	3.5	*1)	Outdoor Temp. 32℃
2	Wall	7.0	-	-	3.5	*1)	Wall Surface 26℃
3	Wall	7.0	-	-	3.5	*1)	Wall Surface 26℃
4	Wall	7.0	160000	-	3.5	*1)	Wall Surface 26℃
5	Wall	5.8	-	160000	5.8	*1)	Wall Surface 26℃
	Floor				11.6	5.8	Floor Surface 26℃

*1)Glass surface 11.6, Others 5.8.
*2)Heat Transfer Coefficient of inner surface
*3)Heat Transmission coefficient except for α_i

that the ventilation for the upper region of the atrium contributes to the cooling of the entire atrium.

No comparison with the experiment has been conducted, but as mentioned above, the results are considered to be reliable to a certain extent. The total amount



J: Solar Radiation [kW/m²]
θ_i: Indoor Temp.[℃]
θ_o: Outdoor Temp.[℃]
θ_{wi}: Temp. of Inner Glass Surface
$\theta_{wi'}$: Temp. of Floor Surface [℃]
A_s: Absorptivity of Solar Radiation
T_s: Permeability of Solar Radiation
α_i: Inner Heat Transfer Coef. [kW/m²]
θ_{ref}: Referance Temp [℃]
K_i: Heat Transmission Coef. except for α_i [kW/m²]

Calculation Method of Inner Surface Temp. [θ_{wi}] on Walls

$$g\alpha_i(\theta_i-\theta_{wi})+K_i(\theta_{ref}-\theta_{wi})+Q+T_m^3\cdot\sigma\cdot\varepsilon_i\sum_j B_{ij}(\theta_{wj}-\theta_{wi})=0 \quad —①$$

θ_{wi} can be solved by using Eq. ①.
Glass surface temp. is calculated at the conditions $\theta_{ref}=\theta_o$, $Q=J\cdot A_s$.
Floor surface temp. is calculated at the conditions $\theta_{ref}=\theta_i'$, $Q=J\cdot A_s\cdot T_s$
Where T_m=300K, σ: Stefan-Boltzmann Const.,
ε_i: Radiation Coef.(=0.95), B_{ij}:Gebhart Absorption Factor.

Fig.3 Solution Method of Inner Surface Temp. for Macroscopic Model

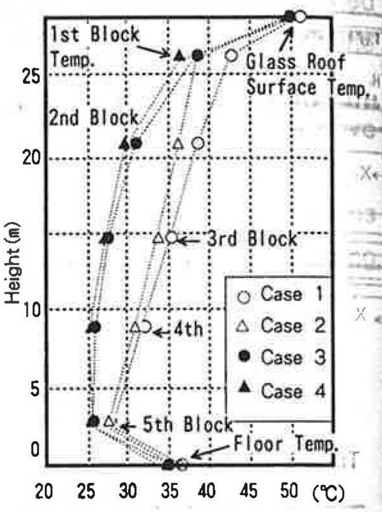
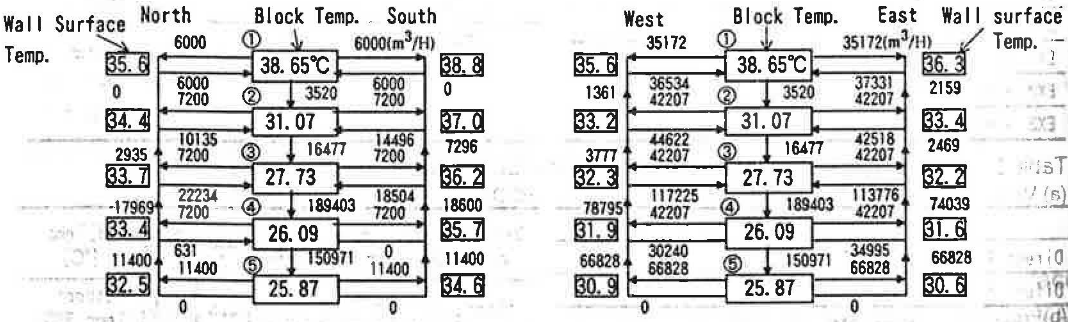


Fig. 4 Results of Macro-study (Temperature Distribution)



Numbers in the figure show the airflow volume.

Fig.5 Results of Macro- Study at the Steady States (Case3, Local Air-conditioning System: On, Vnetilation System at 1st Block : Off)

of heat inflow into this atrium is 880 kW. In this case, the cooling load for the air-conditioning system is calculated to be approximately 40% of that in the case where the temperature of the indoor space is uniformly maintained at 26℃.

3. STUDY BASED ON TURBULENCE SIMULATION (k-ε MODEL)

3.1 General Description of Study

Using the same conditions as applied to the Case 3 based on the macroscopic model mentioned in the previous section, calculations have been conducted by using the k-ε model. At this time, the heat flux determined from the results of the macroscopic study has provided the boundary conditions concerned

Table 4 Conditions for 3 – Dimentions Turbulence Simulation

Mesh Division	$229(X_1)\times 28(X_2)\times 31(X_3)$ for 1/4 Model(south-west area) (2×2 meshes are assignd to one opening.)
Convection Term	QUICK Scheme

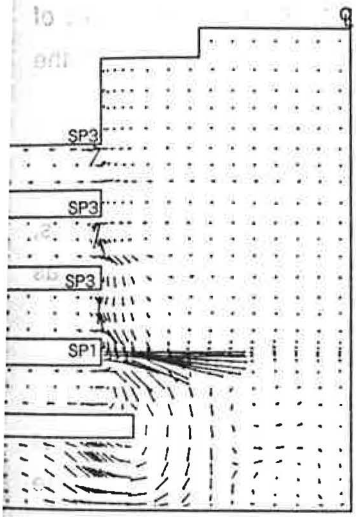


Fig. 6 Airflow Distribution (k- ε model)

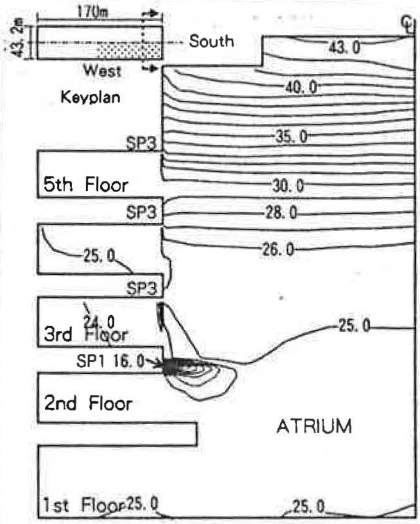


Fig. 7 Temperature Distribution (k- ε model)

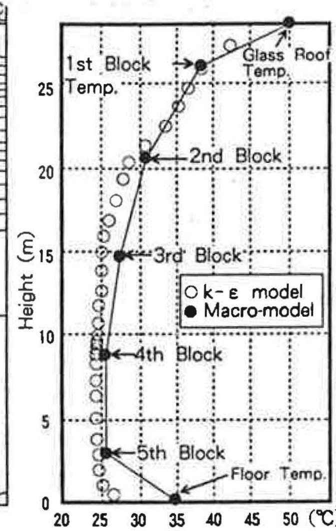


Fig. 8 Comparison between Result of Macro-model and that of k- ε model

with heat transfer at each wall surface. The heat flux is evaluated by multiplying the convective heat transfer coefficient assumed in the macroscopic study by the temperature difference between the block and wall surface obtained from the macroscopic study.

As shown in Fig. 3, with the macroscopic model, the mutual radiation between walls is considered in the calculation process of wall surface temperatures. Therefore the mutual radiation effect can be taken into account to a certain extent in the turbulence simulation. The supply and exhaust air conditions are given in Table 1 and other conditions are indicated in Table 4.

3.2 Results of Simulation based on k- ε Model

Simulation results are shown in Figs. 6 to 8. In contrast to the temperature of the area near the roof which is as high as 43 ℃, the temperature of the area near the floor is around 25 ℃. Due to the effect of supply opening SP3, the air temperature in the passage areas is sufficiently lowered, but since the temperature of the area at the 5th floor is around 30 ℃, some architectural devices have to be designed to protect the space from hot airflow.

In the macroscopic model, the effects of local air-conditioning for the passage areas at the 3rd to 5th floor are assumed as being limited to each floor. However, judging from the air velocity distribution shown in Fig. 6, the effects of local air-conditioning actually extend to the lower blocks, and contribute to the cooling of the entire atrium.

Fig. 8 shows the distribution of temperature as compared with the results of the macroscopic study. There is an approximately 2 ℃ difference at the level of the 3rd block, but as a whole, these results are in agreement.

4. CONCLUSION

From these results of the studies by the combined use of the two models, some conclusions are confirmed with respect to air-conditioning for an atrium as follows :

(1) The temperature of the area near the glass roof is believed to exceed 40 ℃.
(2) Ventilation for the upper region of the atrium is effective for cooling.
(3) At the areas opened to the atrium, local air conditioning system should be set up. Especially at the areas opened to the upper region of the atrium, some architectural devices should be designed to protect the areas from hot airflow.
(4) Where the airflow contributions are appropriate, local air-conditioning system can control temperatures of occupied areas to be in a comfortable range with less energy than if the entire atrium space is uniformly air-conditioned.

NOTE

In a large-scale indoor space in which the horizontal air temperature may be considered uniform except for the regions near walls, the air temperature can be calculated by separating the space into some blocks only in the perpendicular direction. The temperatures of blocks are calculated on account of the following :

(1) airflow (ascending, descending, circulating) along walls,
(2) the effects of turbulent diffusion at block boundaries, and
(3) the effects of convection by blow jet from supply openings.

(Details are given in Togari et al. 1991).

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Numerical Study of an Atrium by Means of a Macroscopic Model and k-ε Turbulence Model

Y. Kondo, D.Eng. **H. Niwa**

ABSTRACT

In designing air-conditioning systems for large-scale indoor spaces, it is important to predict the air velocity and temperature distributions in such spaces so that the indoor climate can be controlled effectively. The indoor climate can be predicted by two numerical simulation methods: one is a rough study using a macroscopic model and the other is a numerical simulation based on a turbulence model. Each method has its limitations. For example, the macroscopic model cannot provide detailed data of the flow and temperature fields, whereas with the k-ε turbulence model it is difficult to determine proper boundary conditions for heat transfer at wall surfaces for the numerical simulation study. This paper describes the results of studies on the indoor climate of a large-scale space by these two methods and explains how the problems involved can be solved by the combined use of the two methods.

INTRODUCTION

There are two numerical simulation methods of predicting the thermal environment of large-scale indoor spaces such as atriums namely, the "macroscopic analysis method" (hereinafter referred to as the "macroscopic model") and airflow simulation based on the "turbulence model" (Murakami *et al.* 1990). When the proper conditions are used, the calculation results of both methods are reasonably precise, and these methods are already being applied to the design and analysis of thermal environments for large-scale indoor spaces.

However, details of the airflow and temperature fields cannot be examined with the results of macroscopic model simulation only. On the other hand, in the case of the turbulence model, the boundary conditions of heat transfer at wall surfaces, which have the most significant effect on the analytical results, often have to be based on rather bold assumptions.

As illustrated in Figure 1, this paper discusses how most of the limitations inherent to each method can be eliminated by making calculations using both methods in combination.

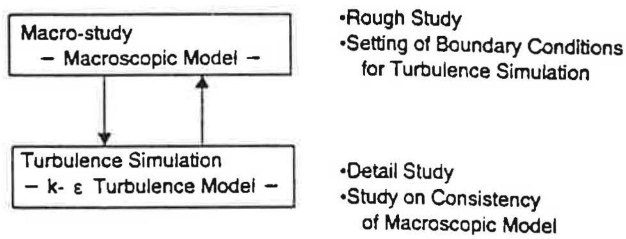
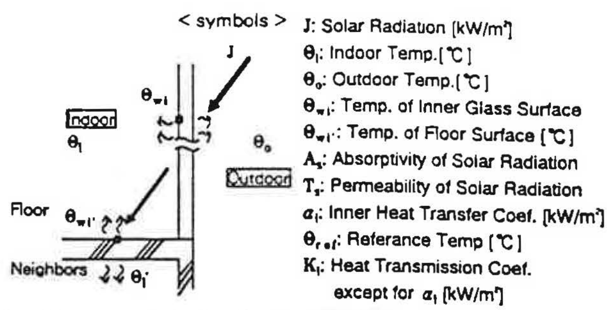


Figure 1 *Relationship between macro-study and turbulence simulation.*



Calculation Method of Inner Surface Temp. [θ_{wi}] on Walls

$$g\alpha_i(\theta_i-\theta_{wi})+K_i(\theta_{ref}-\theta_{wi})+Q+T_m^3\cdot\sigma\cdot\varepsilon_i\sum_j B_{ij}(\theta_{wj}-\theta_{wi})=0 \quad \text{—①}$$

θ_{wi} can be solved by using Eq.①.

Glass surface temp. is calculated at the conditions $\theta_{ref}=\theta_o$、 $Q=J\cdot A_g$

Floor surface temp. is calculated at the conditions $\theta_{ref}=\theta_i'$、 $Q=J\cdot A_s\cdot T_s$

Where T_m=300K, σ: Stefan-Boltzmann Const.、

ε_i: Radiation Coef.(=0.95)、 B_{ij}:Gebhart Absorption Factor.

Figure 2 *Solution method of inner surface temperature for macroscopic model.*

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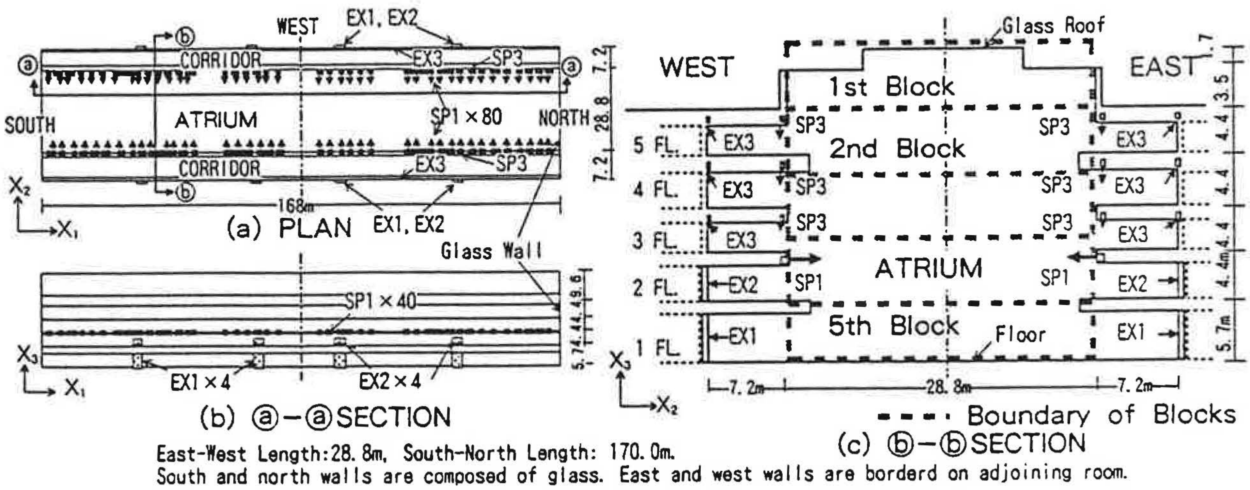

Figure 3 *Objective of analysis.*

Table 1
Case for Macroscopic Model Study

System	Case1	Case2	Case3	Case4	Notes
Local Air-Conditioning System	OFF	OFF	ON	ON	Thermal Load at 2-4 Blocks is -116000 kW
Local Ventilation System at 1st Block	OFF	ON	OFF	ON	Exchange Airflow Volume is 50000 m³/H

STUDY BASED ON MACROSCOPIC MODEL

General Description of Study

This study is based on the block model/wall surface airflow model (Togari *et al.* 1991; see "Note"). Wall surface temperatures are calculated using the formula shown in Figure 2, taking mutual radiation between wall surfaces into consideration.

Conditions for the macroscopic model study are indicated in Tables 1 and 2. The local air conditioning for the passage area for the third to fifth floor and the local ventilation for the region near the ceiling are treated as noted in Table 1. The objective of this present study is the atrium shown in Figure 3.

Results of Macroscopic Study

As shown in Figures 4 and 5, in Case 3, where local air conditioning is assumed for the passage areas at the third to fifth floor, the temperatures of the second to fourth blocks are approximately 6°C to 8°C lower and the temperatures of the first and fifth blocks are 2°C to 4°C lower than in Case 1. Also, in Case 4, where the upper region of the atrium is

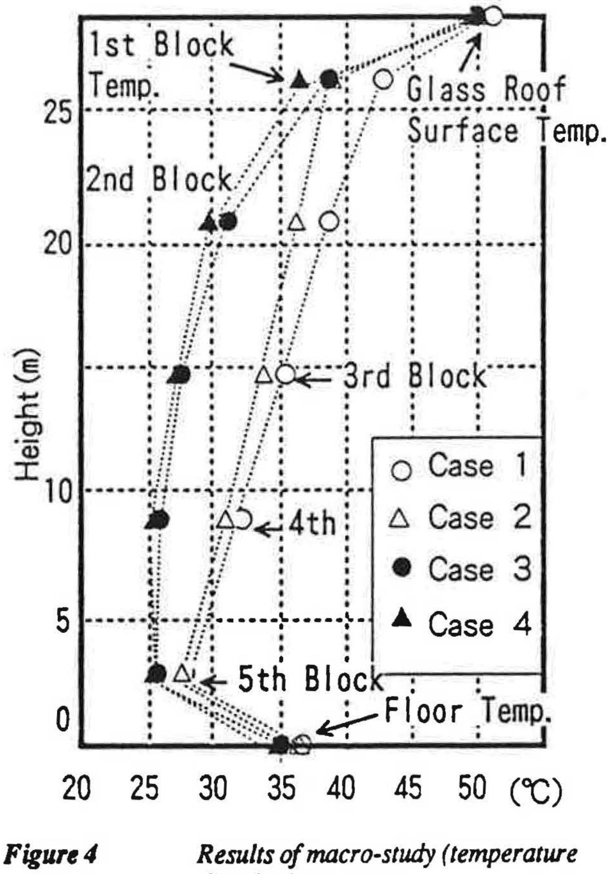

Figure 4 *Results of macro-study (temperature distribution).*

assumed to be ventilated, the temperature in the first block is about 2.5°C lower and that in all other blocks is 0.5°C to 1°C lower than in Case 3. It is shown that the ventilation for the upper region of the atrium contributes to the cooling of the entire atrium.

No comparison with the experiment has been conducted, but, as mentioned above, the results are considered to be reliable to a certain extent. The total amount of heat inflow into this atrium is 880 kW. In this case, the cooling load for the air-conditioning system is calculated to be approximately

Table 2
Conditions of Analysis for Macroscopic Model Study

(a) Value of Solar Radiation [kW/m²]

	South	North	W&E	Horizontal
Direct Radiation	207	0	0	730
Difuse Radiation	54	54	54	108

(b) Properties of Glass Wall and Roof

	Permea-bility	Reflec-tivity	Absorp-tivity	Notes
Glass Wall	0.65	0.06	0.29	Absorption Glass
Glass Roof	0.10	0.50	0.40	Absorption Glass with Blinds

(c) Absorbed Heat of Solar Radiation [kW/m²]

Glass Wall (South Wall)	76	Glass Roof	335
Glass Wall (North Wall)	16	Floor	103
East Wall and West Wall	16	Inner Wall	17

(d) Others

Block no		Height [m]	Supply [m³/H]	Exhaust [m³/H]	α_i *2) [kW/m²]	K_i *3) [kW/m²]	Ref. Temp. [°C]
1	Roof	6.7	50000	50000	3.5	11.6	Outdoor Temp. 32°C
	Wall				3.5	*1)	Outdoor Temp. 32°C
2	Wall	7.0	-	-	3.5	*1)	Wall Surface 26°C
3	Wall	7.0	-	-	3.5	*1)	Wall Surface 26°C
4	Wall	7.0	160000	-	3.5	*1)	Wall Surface 26°C
5	Wall	5.8	-	160000	5.8	*1)	Wall Surface 26°C
	Floor				11.6	5.8	Floor Surface 26°C

*1) Glass surface 11.6, Others 5.8.
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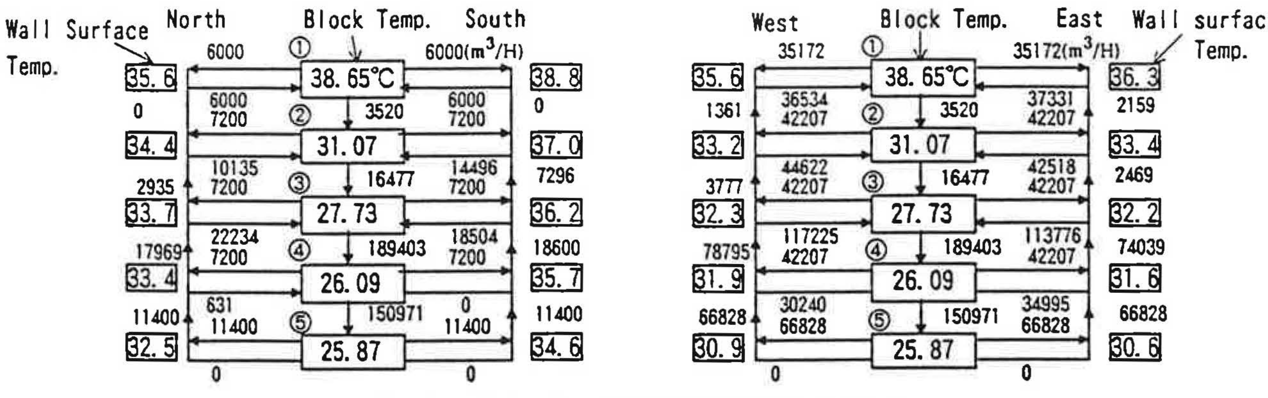

Figure 5 *Results of macro-study at steady states (Case 3, local air-conditioning system on ventilation system at first block off).*

40% of that in the case where the temperature of the indoor space is uniformly maintained at 26°C.

STUDY BASED ON TURBULENCE SIMULATION (k-ε) MODEL

General Description of Study

Using the same conditions as applied in Case 3 based on the macroscopic model, calculations were conducted using the k-ε model. The heat flux determined from the results of the macroscopic study provided the boundary conditions for heat transfer at each wall surface. The heat flux is evaluated by multiplying the convective heat transfer coefficient assumed in the macroscopic study by the temperature difference between the block and wall surface obtained from the macroscopic study.

As shown in Figure 2, with the macroscopic model the mutual radiation between walls is considered in the determination of wall surface temperatures. Therefore, the mutual radiation effect can be taken into account to a certain extent in the turbulence simulation. The supply and exhaust air conditions are given in Table 3 and other conditions are indicated in Table 4.

Table 3
Conditions of Airflow at Supply and Exhaust Openings

Symbol	Type of Openings	Floor	Airflow Volume [m³/H]	Velocity at openings [m/s]	Number of Openings	Airflow temp. [℃]
SP1	supply	2F	2000	3.5	80	16.0
SP3	supply	3-5F	17000	0.7	6	16.0
EX1	exhaust	1F	16000	1.0	8	-
EX2	exhaust	2F	4000	1.0	8	-
EX3	exhaust	3-5F	17000	1.0	6	-

Table 4
Conditions for Three-Dimensional Turbulence Simulation

Mesh Division	229(X_1)×28(X_2)×31(X_3) for 1/4 Model (south-west area) (2×2 meshes are assignd to one opening.)
Convection Term	QUICK Scheme

Results of Simulation Based on k-ε Model

Simulation results are shown in Figures 6 to 8. In contrast to the temperature of the area near the roof, which is as high as 43°C, the temperature of the area near the floor is around 25°C. Due to the effect of supply opening SP3, the air temperature in the passage areas is sufficiently lowered, but since the temperature of the area at the fifth floor is around 30°C, some architectural devices have to be designed to protect the space from hot airflow.

In the macroscopic model, the effects of local air conditioning for the passage areas at the third to fifth floor are assumed as being limited to each floor. However, judging from the air velocity distribution shown in Figure 6, the effects of local air conditioning actually extend to the lower blocks and contribute to the cooling of the entire atrium.

Figure 8 shows the distribution of temperature compared with the results of the macroscopic study. There is an approximately 2°C difference at the level of the third block, but as a whole, these results are in agreement.

CONCLUSIONS

From these results of the studies of the combined use of the two models, some conclusions are reached with respect to air conditioning for an atrium as follows:

1. The temperature of the area near the glass roof is believed to exceed 40°C.
2. Ventilation for the upper region of the atrium is effective for cooling.
3. For areas open to the atrium, a local air-conditioning system should be set up, and some architectural devices

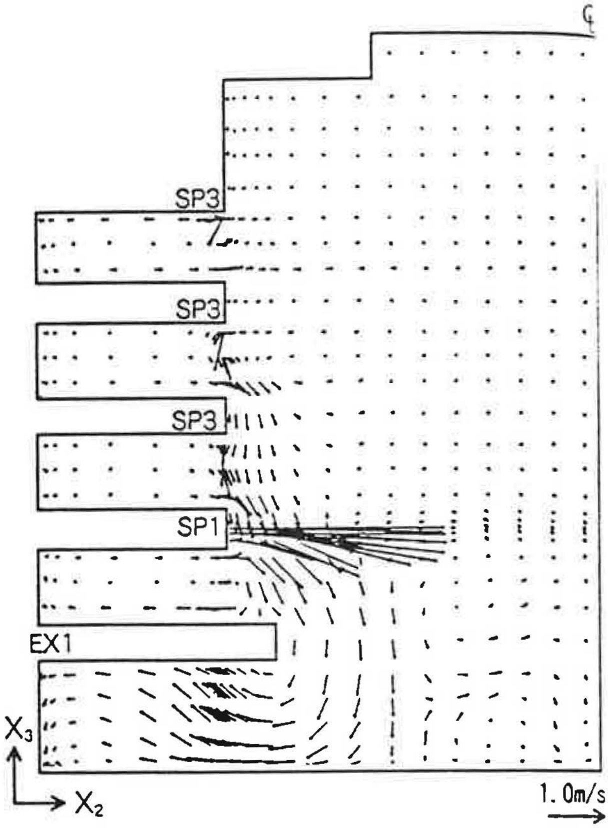

Figure 6 *Airflow distribution (k-ε model).*

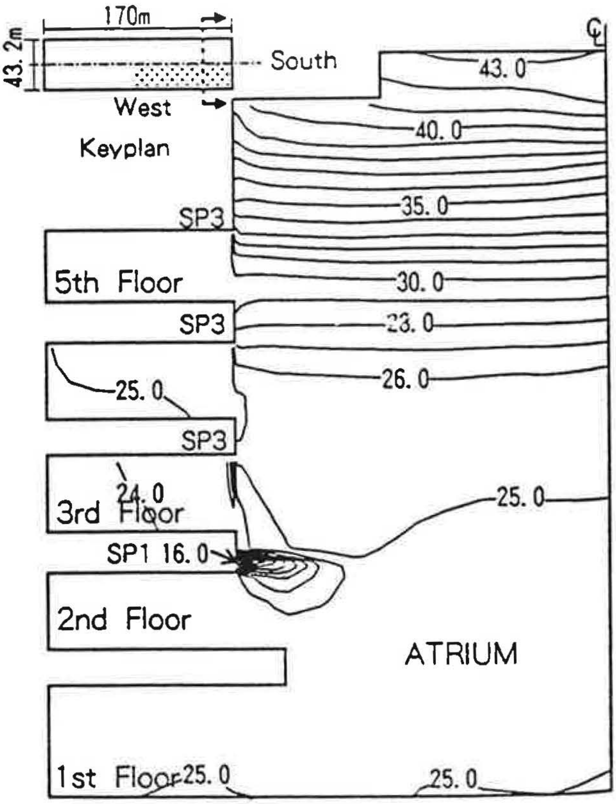

Figure 7 *Temperature distribution (k-ε model).*

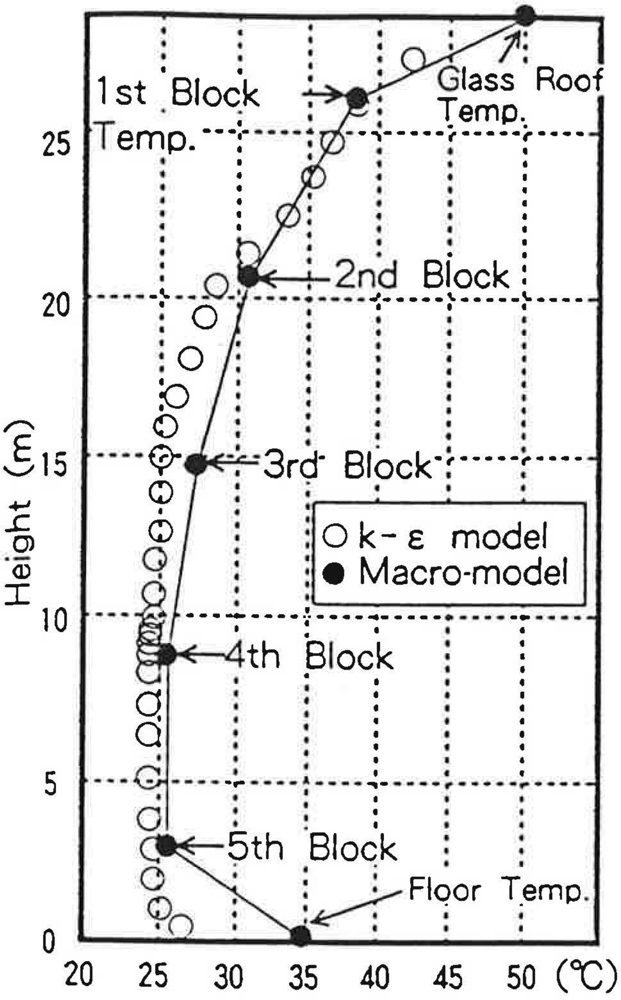

Figure 8 *Comparison between results of macro-model and k-ε model.*

should be designed to protect the areas from hot airflow, especially those open to the upper region of the atrium.

4. Where the airflow contributions are appropriate, a local air-conditioning system can control the temperatures of occupied areas to be in a comfortable range with less energy that if the entire atrium space is uniformly air-conditioned.

NOTE

In a large-scale indoor space in which the horizontal air temperature may be considered uniform except for the regions near walls, the air temperature can be calculated by separating the space into blocks only in the perpendicular direction. The temperatures of blocks are calculated based on the following: (1) airflow (ascending, descending, circulating) along walls, (2) the effects of turbulent diffusion at block boundaries, and (3) the effects of convection by blow jet from supply openings (details are given in Togari *et al.* 1991).

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