Prediction of indoor sol–air temperature in an atrium space with a vertical distribution

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ABSTRACT
This study suggests a computer model capable of predicting thermal environment of an atrium and calculating indoor sol–air temperature, which can evaluate the influence of heat loads that the atrium space puts on the adjoining rooms. The computer model is based on zonal model combined with the solar radiation model using the Monte Carlo method and ray-tracing technique. The accuracy of computer model was validated through scale model test and field measurement. The average relative error of solar radiation model for predicting solar radiation intensity in atrium space was 11.8%. The average relative error of zonal model to calculate vertical air temperature in atrium space was 1.71%, and in all zones the relative error ranged from 1.34 to 2.5%.

INDEX TERMS
Temperature; Solar radiation; Modelling; Natural ventilation

INTRODUCTION
Buildings with an atrium give us visual refreshment as well as economic, cultural and functional benefits. One of the most principle requirements of atriums is to control the environment of an atrium space and adjoining rooms in order to ensure the comfortable indoor condition and to save energy. As for thermal environment, atriums are very susceptible to seasonal or daily outdoor weather condition, and have vertical temperature stratification inside atrium because of it is made of glass. The upper parts of buildings become overheated as most atriums have limited cooling mainly for residential areas in summer. As a buffer zone, atriums reduce the heating load of the adjoining rooms in winter by retaining the heat generated by solar radiation. However, the cooling load of the adjoining rooms increases in summer as the heat from the sun and hot outdoor air heat up inside the atriums. For this reason, atriums require architectural measures and equipment to minimize the cooling load of adjoining rooms and to prevent the overheating caused by thermal stratification.

This paper involves producing a computer model capable of predicting thermal environment of an atrium and calculating indoor sol–air temperature which can evaluate the influence of heat loads that the atrium space puts on the adjoining rooms to provide architectural design data that can improve the thermal environment of atrium buildings and to use energy efficiently.

METHODS
The computer model is a combination model based on the zonal model (Togari *et al.*, 1993) for the prediction of vertical air temperature, the natural ventilation model and the solar radiation model for the analysis of three-dimensional solar short-wave radiation intensity in an atrium.

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Solar Radiation

For the accurate prediction of distribution of solar short-wave radiation intensity that goes through an atrium, Monte Carlo method (Neumann *et al.*, 1945) and Ray tracing technique are used. Linear congruential method (Lehmer, 1951) is used to generate photons following the Monte Carlo method. In developing a photon-generator that has uniform probability distribution with linear congruential method, inverse transformation method comes in to turn uniform probability distribution into desired distribution.

Natural Ventilation

Natural ventilation is the flow of outdoor air due to wind and thermal pressure through intentional openings on the building's shell.

The most commonly used expression for the airflow rate through an opening is as follows:

$$V_0 = C_\mathrm{d} \times A \times \sqrt{\frac{2\Delta P}{\rho}} \quad (1)$$

where C_d is the discharge coefficient for opening [–], A the cross-sectional area of opening [m^2], • P the pressure difference across opening [Pa], and ρ the air density [$\mathrm{kg/m}^3$].

The pressure difference through opening makes outside air come in, as the force of natural ventilation. The pressure difference is caused by wind and stack effects:

$$\text{Wind pressure:} \quad P_\mathrm{w} = 0.5 \times \rho \times C_p \times V^2 \quad (2)$$

$$\text{Stack effect:} \quad \Delta P_\mathrm{s} = \rho_\mathrm{i} \times g \times (h - h_\mathrm{NPL}) \times \frac{(T_\mathrm{i} - T_\mathrm{o})}{T_\mathrm{o}} \quad (3)$$

where V is the wind speed [m/s], h the height of observation [m], h_NPL the height of neutral pressure level [m], T_i the indoor air temperature [K] and T_o the outdoor air temperature [K].

Vertical Air Temperature

Heat balance equations of a structure comes up as follows to calculate the inner surface temperature which used as a boundary condition to be factored into the equation for vertical air temperature of an atrium space:

$$M_\mathrm{structure} \cdot \frac{\mathrm{d}T}{\mathrm{d}t} = q_\mathrm{r} + q_\mathrm{r} + \mathrm{Sol}_\mathrm{in} + q_\mathrm{CD} \quad (4)$$

$$M_\mathrm{structure} \cdot \frac{\mathrm{d}T}{\mathrm{d}t} = \rho \cdot C \cdot \Delta V \cdot \frac{\mathrm{d}T}{\mathrm{d}t} \quad (5)$$

$$M_\mathrm{structure} \cdot \frac{\mathrm{d}T}{\mathrm{d}t} = q_\mathrm{o} - q_\mathrm{CD} \quad (6)$$

where q_c is the convective heat flow rate [W], q_r the radiative heat flow rate [W], q_CD the transmissive heat flow rate [W], Sol_in the solar short-wave radiation [W] and q_o the external heat flow rate [W].

Finite difference method is used to discretize the equations. Figure 1 represents the schematic of the air movement between vertically adjacent zones.

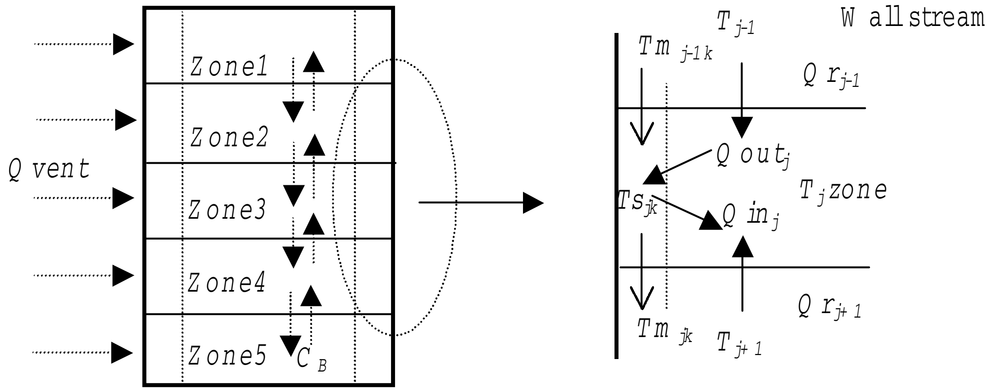


Figure 1 Schematic of the air movement between zones.

The equations of air volume and heat balance between zones are below. The equations will be used for the calculation of vertical air temperature distribution:

$$\sum_{k=1}^{NK}(Q\mathrm{in}_{jk} - Q\mathrm{out}_{jk} + Q\mathrm{vent}_{jk}) + Q\mathrm{r}_{j+1} - Q\mathrm{r}_j = 0 \quad (7)$$

$$\begin{aligned} M\frac{\mathrm{d}T_j}{\mathrm{d}t} &= \sum_{k=1}^{NK} cpr \cdot Q\mathrm{in}_{jk} \cdot (T\mathrm{m}_{jk} - T_j) \\ &+ cpr \cdot Q\mathrm{r}_{j+1} \cdot (T_{j+1} - T_j), [Q\mathrm{r}_{j+1} \rangle 0] \\ &+ cpr \cdot Q\mathrm{r}_j \cdot (T_{j-1} - T_j), [Q\mathrm{r}_j \rangle 0] \\ &+ C_\mathrm{B} \cdot A_\mathrm{B} \cdot [(T_{j+1} - T_j) + (T_{j-1} - T_j)] \\ &+ cpr \cdot Q\mathrm{vent}_{jk} \cdot (T_\mathrm{o} - T_j), [Q\mathrm{vent}_{jk} \rangle 0] \quad (8) \end{aligned}$$

where Q_{in} is the ascending airflow rate (wall surface current) [m^3], Q_{out} the descending airflow rate (wall surface current) [m^3], Q_r the airflow rate between vertically adjacent zones [m^3], Q_{vent} the airflow rate in opening [m^3], C_B the heat transfer factor between zones [W/m^2/K], A_B the floor area of zones [m^2], T_j the air temperature of the jth zone [K] and T_m the average air temperature of ascending airflow [K].

Indoor Sol–Air Temperature

Indoor_sol–air temperature is introduced to evaluate the impact of heat load that an atrium space puts on the adjoining rooms. The indoor_sol–air temperature brings in the concept of sol–air temperature:

$$T_{\mathrm{sol}} = T_\mathrm{o} + \alpha_\mathrm{o} \cdot (I_\mathrm{t} / h_\mathrm{o}) - \varepsilon_\mathrm{o} \cdot (\Delta R / h_\mathrm{o}) \quad (9)$$

where T_{sol} is the sol–air temperature [K], α_o the absorptance of external surface for solar radiation [–], I_t the total solar radiation incident on surface [W/m^2], h_o the external heat transfer coefficient [W/m^2/K] and ε_o the hemispherical emittance of external surface [–].

In Eqn (9), long-wave radiation ΔR is ‘0’ on the surface of vertical wall (ASHRAE, 1997). Indoor air of atrium space is assumed to be outdoor air in the main building. Indoor sol–air temperature of the main building is as calculated follows:

$$T_{\mathrm{I\_SAT}} = T_j + \alpha_\mathrm{i} \cdot (I_\mathrm{t} / h_\mathrm{i}) \quad (10)$$

where α_o is the absorptance of internal surface for solar radiation [–] and h_o the internal heat transfer coefficient [W/m^2/K].

VALIDATION OF COMPUTER MODEL

Solar Radiation Intensity

Atrium scale model test

Atrium scale model used to validate a solar radiation model having sensors to measure the distribution of solar radiation intensity on the inner surface of an atrium. The measurement values of solar radiation intensity are used to compare with the calculation values by a solar radiation model. The reflectance of the inner surface of the atrium scale model is 84%, the transmittances of solar radiation going through a glass pyramid skylight are 92.3, 67.3 and 34.6%, depending on the materials of skylights.

Variables in this measurement are Well Index (Baker and Steemers, 1993) and transmittance of solar radiation in the skylights. Table 1 presents 12 types of simulations of a solar radiation model and its measurements.

Table 1 Simulation cases

Case	Well index	Transmittance [%]	Case	Well index	Transmittance [%]
1	2.4	92.3	7	1.2	92.3
2	2.4	67.3	8	1.2	67.3
3	2.4	34.6	9	1.2	34.6
4	1.8	92.3	10	0.6	92.3
5	1.8	67.3	11	0.6	67.3
6	1.8	34.6	12	0.6	34.6

Calculating conditions

The results of measurement become the input conditions including outdoor weather and material properties. The composition of grids on each surface for calculating is 9×9 on the floor and 9×12 on each wall.

Preliminary simulation was designed to determine the number of photons injected in Monte Carlo method testing. As a result, the number of photons for direct solar radiation is 100 000 and photons for diffuse solar radiation are rounded up to 10 000, as shown in Figure 2.

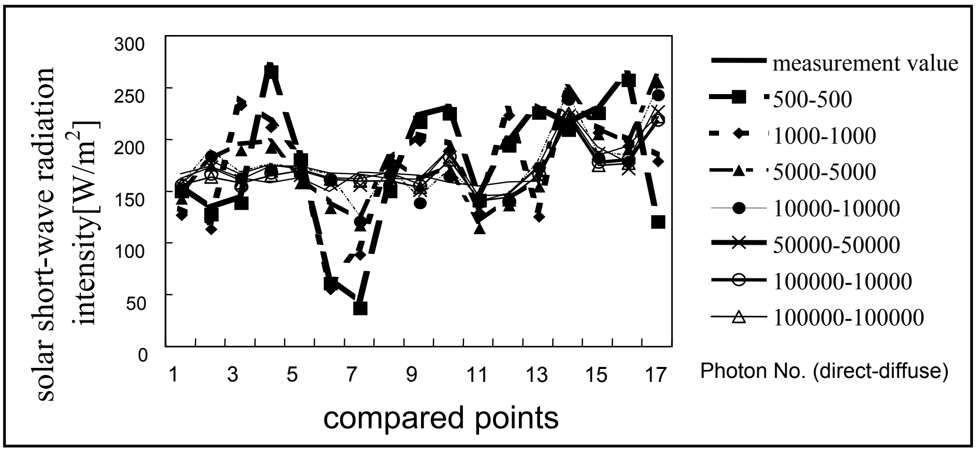


Figure 2 Preliminary simulation to determine the number of photons.

Comparing measurement with calculation results

The accuracy of a solar radiation model is evaluated by the relative error that comes up in the following equation:

$$Er = \sum_{i=1}^{n} \frac{(M_i - A_i)}{M_i} \times \frac{1}{n} \times 100[\%] \quad (11)$$

where A_i represents calculation values, M_i the measurement values, n the sum of measurement points. The relative error ranges from 9 to 17% with average of 11.8%.

Vertical Air Temperature

Field measurement

In springtime, the measurement is kept in a four-sided atrium to validate a zonal model that predicts the vertical distribution of air temperature in atrium space. Atrium is located in 37.34^{o} of latitude, 126.58^{o} of longitude and 85.5 m in altitude. The solar radiation transmittance of skylight is 32%.

Calculating conditions

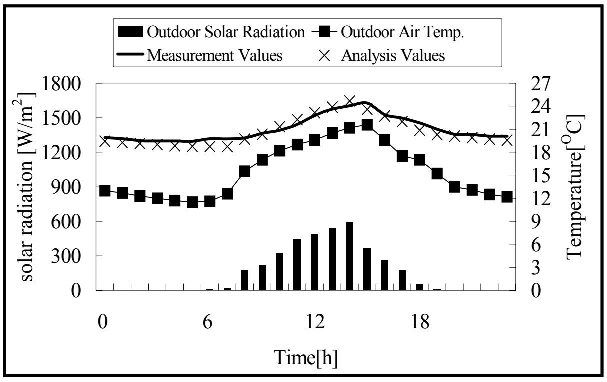
The atrium is divided up to five vertical zones with the same height for the calculation of vertical distribution of air temperature. Heat transfer coefficient (C_B) between the zones is set at 2.326 W/m^2/K with the temperature high in upper zone and at 100 W/m^2/K with temperature low in upper zone for the simplified computer program process.

Ventilation rate is set at 0.8 ACH by default. Other input factors including the outside weather conditions are obtained from the measurement results.

Comparison of measurement and calculation results

The results from measured and calculated vertical air temperature are presented in Figures 3–7. As time goes by, the calculated air temperature is synchronized with the measured ones.

The margin of error for measured and calculated air temperature is ±1.3^{o}C in all days, and for the time line between 09:00 and 18:00 hrs that has a margin of error of ±0.7^{o}C. The average relative error of calculated results in comparison with the measured ones is 1.71% of the entire zone with each zone varying from 1.34 to 2.5%.



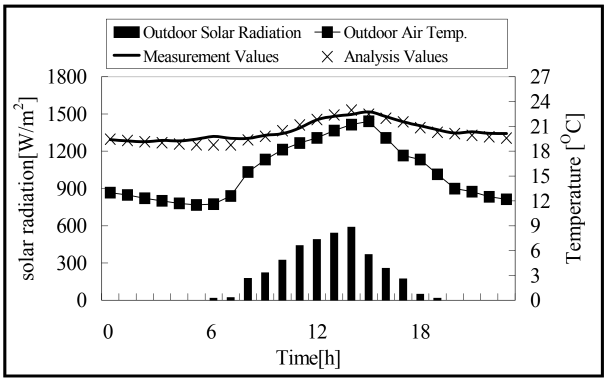


Figure 3 Comparing measurement with calculation results (zone 1; height 15.48 m).

Figure 4 Comparing measurement with calculation results (zone 2; height 12.04 m).

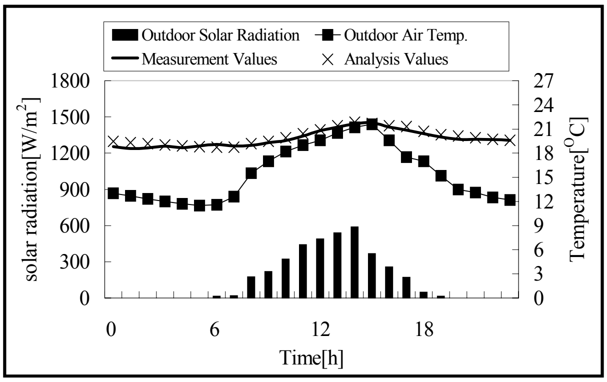


Figure 5 Comparing measurement with calculation results (zone 3; height 8.60 m).

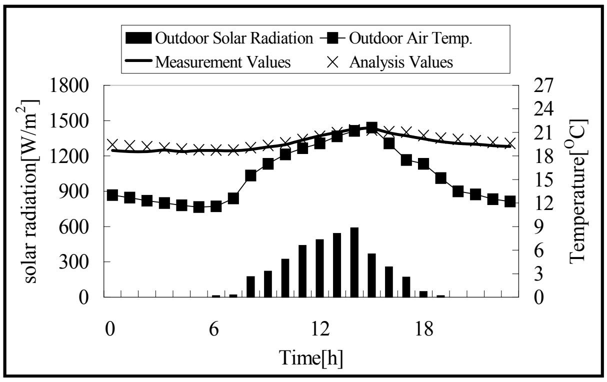


Figure 4 Comparing measurement with calculation results (zone 4; height 5.16 m).

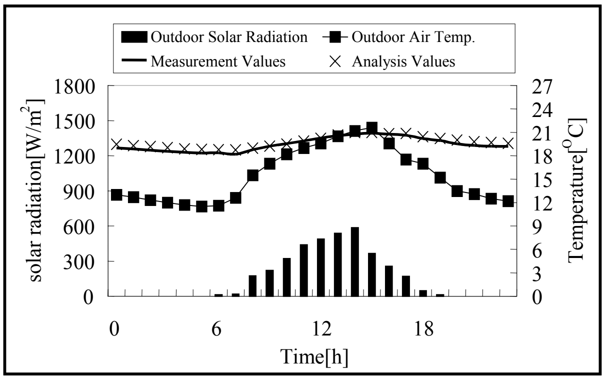


Figure 7 Comparing measurement with calculation results (zone 5; height 1.72 m).

CONCLUSION

In this paper, a computer model that can predict thermal environment in atrium buildings through the combination of zonal model, natural ventilation model and three-dimensional solar radiation model was presented.

Atrium scale model test and field measurement were conducted to validate the accuracy of the computer model and the results are as follows: The average relative error of the predicted values of solar short-wave radiation intensity compared with the measured values is 11.8% and the average relative error of predicted vertical air temperature is 1.71%, in all zones and the relative error ranges from 1.34 to 2.5%. In addition, the distribution of indoor sol–air temperature was suggested to evaluate the effects of heat load an atrium puts on the adjoining rooms. The indoor sol–air temperature is measured using Eqn (10).

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