DYNAMIC SIMULATION OF ATRIUM THERMAL ENVIRONMENT AIDING BUILDING DESIGN

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ABSTRACT

Atrium is becoming a popular common space in commercial buildings nowadays. In planning the thermal environment and air-conditioning system for an atrium, it is necessary to calculate a cooling load for the occupied zone and to predict the vertical temperature distribution. Besides, the thermal environment varies with time, so dynamic thermal environment analysis, including prediction of vertical temperature, is required.

The building design process of the atrium consists of several different stages. The aim of this research is to develop a modular for dynamic simulation of atrium thermal environment in the stage of architecture design. Except for heat transfer by conduction and convection, long-wave radiation, solar radiation and indoor thermal disturbance are also used to describe the atrium thermal environment in the simulation. The development is based on the building dynamic simulation tool DeST.

The authors also apply this method to an atrium that is affected by transmitted solar radiation, and analysis the simulation results.

KEYWORDS

Atrium, Dynamic simulation, Block Model, DeST

INTRODUCTION

As a kind of large space, atriums are adopted extensively in building design which typically emphasizes openness and natural light. The atrium has the characteristics different from the general room space, such as big volume and large area of glass roof and walls. Therefore a lot of solar radiation comes into the atrium through these enclosures. Heated by the sunshine, the inner surface of atriums can exchange heat with other surfaces or the air by long-wave radiation, convection and conduction. Besides, the atrium is usually very high. Therefore the vertical temperature differences tend to be large in the daytime of summer. Furthermore, natural and mechanical ventilation are usually used in atriums which make the thermal environment much more complicated.

The building design process of the atrium consists of several different stages. In each of the design stage, the key point of design and the problems to be solved are different. For example, in the stage of architecture design, the architecture appearance, daylighting, fabric design and natural ventilation are the main problems to be solved. But in the stage of HVAC system design, the air conditioning form, the terminal of the system, the distribution of inlets and outlets, and the amenity in occupied zone are important.

In the stage of architecture design, the function of an energy simulation software to assist designers is:

- ★ Aiding architecture appearance design;
- ★ Aiding building fabric design;
- ★ Aiding daylighting design;
- ★ Aiding natural ventilation design;
- ★ Calculation of annual cooling/heating load.

In the stage of HVAC design, the function of an energy simulation software to assist designers is:

- ★ Sizing the capacity of equipment of HVAC system;
- ★ Aiding HVAC system form design;
- ★ Aiding terminal equipment design of HVAC system;
- ★ Predicting the temperature distribution in occupied zone;
- ★ Predicting the energy consumption of HVAC system.

As the key point in each design stage is different, we need to find the different method for each stage to simulate the annual thermal environment and energy consumption of the atriums. In this paper, we explain the simulation method in architecture design stage, and we add this model into DeST (Designer's Simulation Toolkits), so that the annual dynamic simulation of atriums realized.

REVIEW OF THE STUDY ON ATRIUM SIMULATION METHOD

The study on simulation method of atriums develops continuously, which can be divided into several types:

Lumped parameter method

This method is widely used in practice application. It assumes the temperature in atrium is homogeneous and the air in whole space is considered as only one node. This method is simple, timesaving, and can be applied in the dynamic simulation. However it is too rough, its basic assumption does not agree with the characteristics of the thermal environment of atriums, and it also can not describe the temperature distribution of atriums.

CFD

CFD (Computational Fluid Dynamics) is widely used in the numerical calculation of atrium's thermal environment which is excel at predicting flow field in a space. The study by CFD can be divided into the common simulation method and associated simulation method.

The common simulation method can not calculate the complicated solar radiation which the interior surfaces of the atrium get. The solar radiation is ignored, or it is only distributed uniformly on the surface.

The associated simulation method combines solar radiation with heat convection and conduction. Using Monte Carlo method to calculate solar radiation, Shinsuke Kato (1995) simulated a 130m height atrium by CFD and analyzed the air flow and temperature distribution in different weather conditions. Jingsan Du (2002) calculated the surface heat gain from solar radiation in atriums by numerical calculation, and he developed an associated simulation program based on PHOENICS3.3.

CFD use detailed models to simulate the heat gain from solar radiation, flow field and longwave radiation. Therefore it can give a comprehensive result of thermal environment of atriums. However, it is difficult to define boundary condition. Also, it is time-consuming and is difficult to get a convergent result, which makes it only be used in the steady simulation.

Zonal Model

The main idea of zonal model is to divide the atrium into several zones. The density and temperature of each zone are homogeneous. We establish the mass balance and energy balance equations, and the temperature distribution and air flow between zones can be solved.

Zonal model has much fewer nodes than CFD, so its computational time is not as long as CFD. Also, zonal model provide more detailed information than lumped parameter method, such as temperature distribution et al. Therefore, this model has the characteristics both simple calculation and relatively detailed description of thermal environment of atriums.

It is practical to simulate the thermal environment of atriums by zonal model. But there are still many problems. For example, researchers do not attach importance to the simulation of enclosures of atriums, and they also do not consider the influence between the atrium and its adjacent rooms.

DYNAMIC SIMULATION METHOD OF ATRIUMS BASED ON DeST

The dynamic building thermal process model of DeST bases on state-space method. The dynamic thermal model is the foundation to describe the physics of building thermal environment and its control systems.

In the stage of architecture design, we use Block Model to predict vertical temperature distribution which is incorporated into DeST. The supply airstreams of HVAC system is ignored, for in this stage the HVAC system has not been designed.

The space is vertically divided into several zones and the temperature of occupied zone is set by designers.

Through the simulation of thermal environment of the atrium in architecture design stage, the heating/cooling load of occupied zones and the vertical temperature distribution can be calculated. The results are helpful for the design of fabric, daylighting and natural ventilation, and they also help the designers size the capacity of equipment of HVAC system in next stage.

HEAT DISTURBANCES IN ATRIUMS

In all the heat disturbances influencing thermal environment of atriums, temperature of adjacent rooms, outdoor and ground temperature, wind velocity and direction, longwave radiation between building and sky have been well considered in the DeST, so we will give unnecessary details. We focus on the calculation of the interior heat sources, solar radiation and longwave radiation in the atrium.

Interior heat sources

The interior heat sources of atriums are produced by occupant, lighting and equipment. Some part of heat is transferred to air by convection, and the other is transferred to interior surfaces of atrium by longwave radiation (see Table 1). The longwave radiation is distributed to the inner surfaces with fixed ratios, which are shown in Table 2.

Table 1

	LONGWAVE RADIATION (%)	CONVECTION (%)
Equipment	30	70
Occupant	50	50
Lighting	70	30

Table 2

	Total Longwave radiation (%)	Around (%)	Ceiling (%)	Floor (%)
Equipment	30	24	3	3
occupant	50	40	5	5
Lighting	70	56	7	7

Solar radiation

Solar radiation consists of two parts: direct and diffuse solar radiation. The calculations of two parts are different.

- Direct solar radiation

The direct solar radiation got by exterior surface can be calculated follow two steps:

1) Calculation of the intensity of direct solar radiation on the exterior surface I_d:

$$I_d = I_{dn} \cdot \cos i \tag{1}$$

2) Calculation of facular ratio of the exterior surface $Ratio$.

The direct solar radiation for exterior surface is obtained by Equation 2.

$$Q = I_d \cdot S \cdot Ratio \cdot \alpha \tag{2}$$

For transparent enclosures, such as skylight, we need to calculate the distribution of solar radiation entering into the atrium. It is assumed that the direction of sunlight does not change when it passes through the window. The intensity of direct solar radiation got by inner surface can be calculated:

$$I_i = I_{dn} \cdot \cos i \cdot T_\tau \tag{3}$$

The following equation is used to calculate the direct solar radiation got by inner surface:

$$Q_i = I_i \cdot S_i \cdot Ratio_i \cdot \alpha_i \tag{4}$$

The transmission ratio T_τ and the facular ratio of inner surface $Ratio_i$ can be calculated by DeST. In Equation 4, we assume the absorptive ratio of inner surface α_i to be 1.

- Diffuse solar radiation

The intensity of diffuse solar radiation should be calculated first. The diffuse solar radiation absorbed by the exterior surface can be from the sky, ground surface and other buildings. The quantity of diffuse solar radiation is related to the viewfactors of the exterior surface to the sky, ground surface and other buildings (F_s, F_g and F_b).

$$F_\mathrm{s} + F_\mathrm{g} + F_\mathrm{b} = 1 \tag{5}$$

The total intensity of diffuse solar radiation $I_\mathrm{j,d}$ can be calculated as following equations:

$$I_\mathrm{j,s} = F_\mathrm{s} \cdot I_\mathrm{s,s} \tag{6}$$

$$I_\mathrm{j,g} = F_\mathrm{g} \rho_\mathrm{g} I_\mathrm{sh} \tag{7}$$

$$I_\mathrm{j,b} = F_\mathrm{b} \rho_\mathrm{b} I_\mathrm{b} \tag{8}$$

$$I_\mathrm{j,d} = I_\mathrm{j,s} + I_\mathrm{j,g} + I_\mathrm{j,b} \tag{9}$$

If the diffuse solar radiation from other buildings is ignored:

$$F_\mathrm{s} = \frac{1}{2} + \frac{1}{2}\cos\theta \tag{10}$$

$$F_\mathrm{g} = \frac{1}{2} - \frac{1}{2}\cos\theta \tag{11}$$

The intensity of diffuse solar radiation which passes through the window $I_{j,window}$ can be calculated by Equation 12.

$$I_{j,window} = I_{j,d} \cdot T_{60} \tag{12}$$

T_{60} is the transmission ratio when the incident angle of direct solar radiation is 60 degree. In DeST, We assume that T_{60} is the transmission ratio of the diffuse solar radiation.

The diffuse solar radiation coming into the atrium can be calculated by Equation 13.

$$Q_{j,window} = I_{j,window} \cdot S_{window} \tag{13}$$

Then we distribute the entering diffuse solar radiation to each inner surface (see Equation 14).

$$Q_{i,diff} = Q_{j,window} \cdot F_{j,i} \tag{14}$$

The viewfactor $F_{j,i}$ is calculated by Monte Carlo method.

Longwave radiation

- Viewfactor

The viewfactor $F_{i,j}$ is calculated by Monte Carlo method in DeST. Each surface emits limited rays instead of the real process of emitting innumerable rays, and the viewfactor can be calculated based on the trace of the rays.

- Absorption factor

When surface i emits radiation, surface j finally receives some of them after many times of absorption and reflection. We define the ratio of radiation received by surface j to the original radiation emitted by surface i as the absorption factor $B_{i,j}$.

$$B_{i,j} = \varepsilon_j F_{i,j} + \sum_{m=1}^{n} B_{m,j} F_{i,m} \rho_m \tag{15}$$

If there are n surfaces in a atrium, Equation (16) is created and all the absorption factors can be solved.

$$\begin{bmatrix} F_{1,1}\rho_1 - 1 & F_{1,2}\rho_2 & \cdots & F_{1,n}\rho_n \\ F_{2,1}\rho_1 & F_{2,2}\rho_2 - 1 & \cdots & F_{2,n}\rho_n \\ \vdots & \vdots & \ddots & \vdots \\ F_{n,1}\rho_1 & F_{n,2}\rho_2 & \cdots & F_{n,n}\rho_n - 1 \end{bmatrix} \begin{bmatrix} B_{1,1} & B_{1,2} & \cdots & B_{1,n} \\ B_{2,1} & B_{2,2} & \cdots & B_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ B_{n,1} & B_{n,2} & \cdots & B_{n,n} \end{bmatrix} = \begin{bmatrix} -\varepsilon_1 F_{1,1} & -\varepsilon_2 F_{1,2} & \cdots & -\varepsilon_n F_{1,n} \\ -\varepsilon_1 F_{2,1} & -\varepsilon_2 F_{2,2} & \cdots & -\varepsilon_n F_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ -\varepsilon_1 F_{n,1} & -\varepsilon_2 F_{n,2} & \cdots & -\varepsilon_n F_{n,n} \end{bmatrix} \tag{16}$$

We define total radiative exchange areas $C_{i,j}$ as following Expression:

$$C_{i,j} = \varepsilon_i S_i B_{i,j} = \varepsilon_j S_j B_{j,i} = C_{j,i} \tag{17}$$

And also we can get an equation set from (17):

$$\begin{bmatrix} \varepsilon_1 S_1 & 0 & \cdots & 0 \\ 0 & \varepsilon_2 S_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \varepsilon_n S_n \end{bmatrix} \begin{bmatrix} B_{1,1} & B_{1,2} & \cdots & B_{1,n} \\ B_{2,1} & B_{2,2} & \cdots & B_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ B_{n,1} & B_{n,2} & \cdots & B_{n,n} \end{bmatrix} = \begin{bmatrix} C_{1,1} & C_{1,2} & \cdots & C_{1,n} \\ C_{2,1} & C_{2,2} & \cdots & C_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ C_{n,1} & C_{n,2} & \cdots & C_{n,n} \end{bmatrix} \quad (18)$$

- Net radiation

The net radiation means the difference between effective radiation and absorptive radiation.

The net radiation between two surfaces $Q_{i,j}$ is calculated by Equation 19.

$$Q_{i,j} = -Q_{j,i} = C_{ji}E_{bj} - C_{ij}E_{bi} \quad (19)$$

The net radiation between surface i and all other surfaces is calculated by Equation 20.

$$\begin{aligned} Q_{net,i} &= \sum_{j,j\neq i}(C_{ji}E_{bj} - C_{ij}E_{bi}) \\ &= \sum_{j,j\neq i} C_{ij}(E_{bj} - E_{bi}) \\ &= \sum_{j,j\neq i} C_{ij}\sigma(T_j^4 - T_i^4) \\ &= \sum_{j,j\neq i} C_{ij}\sigma(T_j^2 + T_i^2)(T_j + T_i)(T_j - T_i) \end{aligned} \quad (20)$$

Because the expression $(T_j^2 + T_i^2)(T_j + T_i)$ does not change much in the condition of building thermal environment calculation, so we assume T as a fixed value 20℃.

And the coefficient of heat transfer of longwave radiation hr_{ij} can be defined as following expression:

$$hr_{ij} = C_{ij}\sigma(T_j^2 + T_i^2)(T_j + T_i) = 5.7C_{ij} \quad (21)$$

Substituting this expression into equation (20), the following equation is obtained:

$$Q_{net,i} = \sum_{j,j\neq i} C_{ij}\sigma(T_j^4 - T_i^4) = \sum_{j,j\neq i} hr_{i,j}(T_j - T_i) \quad (22)$$

BLOCK MODEL FOR PREDICTING VERTICAL TEMPERATURE DISTRIBUTION IN ATRIUMS

In this paper we use Block Model (S Togari et al. 1993; Huang Chen et al. 1999) to calculate the vertical temperature distribution in atriums. It is assumed that the following condition to be the major factors causing vertical temperature differences:

1. In winter, the exterior glass wall is cooled and the descending air current generated makes a vertical temperature difference.
2. The upper part of the atrium is heated by the sunshine entering through the skylight, resulting in a considerable vertical temperature difference.
3. The vertical temperature distribution is formed by the cooling of occupied zone or by an inadequate hot air supply.

In order to make it possible to quantitatively evaluate the influence of the factors mentioned above, the Block Model consists of three parts:

The first is the “wall surface current model” for evaluating the descending (or ascending) current flowing along the vertical wall surface. The second is the “primary airstream evaluation model”, which handles the airstreams discharged from outlets as non-isothermal free jets to evaluate their influence on vertical temperature distribution. Last is the “heat transfer factor C_B model” for evaluating the heat transfer caused by the temperature difference vertically adjacent zones. In the stage of architecture design, we do not use “primary airstream evaluation model”，for the HVAC system is still not designed. The calculation procedure is showed as follows:

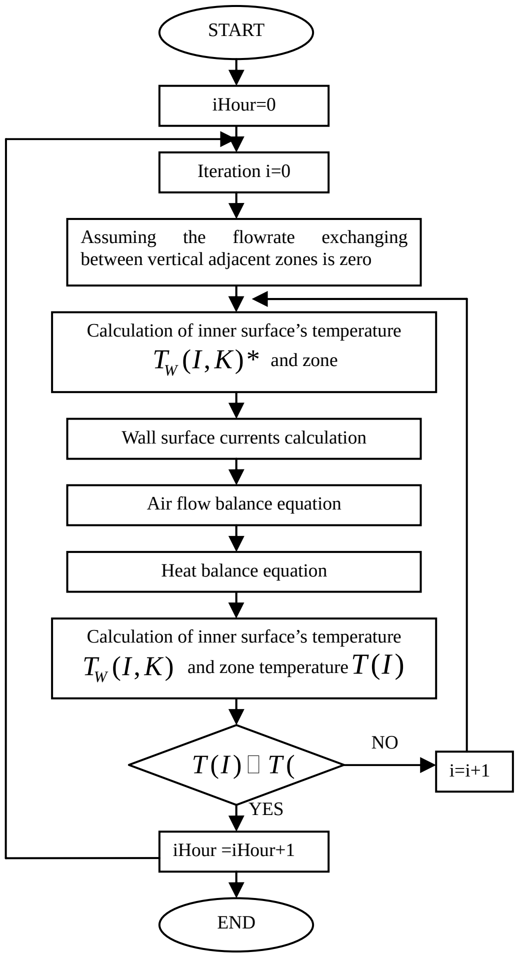

Figure 1 Calculation procedure

Wall surface current model

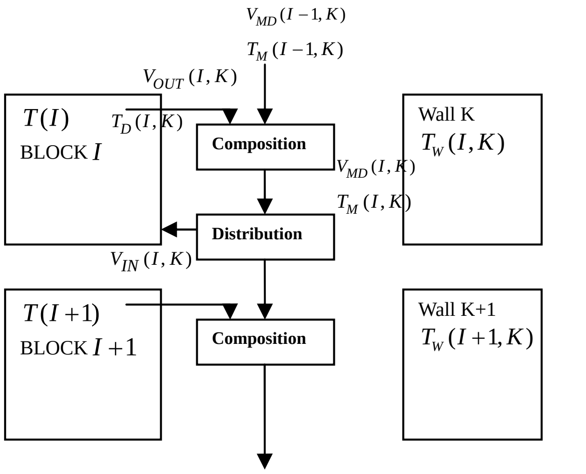

Figure 2 Wall surface current model

Let us take the case where the surface temperature $T_W(I,K)$ of wall K is lower than the zone air temperature $T(I)$. It is assumed that heat flow $q_W(I,K)$, occurs from zone (I) to the wall and at the same time a descending current occurs along the wall. Let the average temperature of the descending current be $T_D(I,K)$. As the temperature drop is caused by the heat flow to the wall, heat balance equations are represented as follows:

$$q_W(I,K) = \alpha_C(I,K)\cdot A_W(I,K)\cdot[T(I)-T_W(I,K)] \\ = c\cdot\rho\cdot V_{OUT}(I,K)\cdot[T(I)-T_D(I,K)] \qquad (23)$$

The average temperature $T_D(I,K)$ of the descending current is approximately represented with the following expression:

$$T_D(I,K) = 0.75\cdot T(I) + 0.25\cdot T_W(I,K) \qquad (24)$$

Substituting this relation into Equation 23, the following equation is obtained:

$$V_{OUT}(I,K) = \frac{4\cdot\alpha_C(I,K)\cdot A_W(I,K)}{c\cdot\rho} \qquad (25)$$

As in zone (I), the descending current flowing from zone (I-1) along the wall (air volume $V_{MD}(I-1,K)$, temperature $T_M(I-1,K)$) is added to the descending current generated in this zone. Temperature $T_M(I,K)$ and air volume $V_M(I,K)$ of the "composite descending current" are obtained from the following equation, where $c\cdot\gamma$ if each descending current component is omitted on the assumption that they are nearly equal to each other.

$$V_M(I,K) = V_{MD}(I-1,K) + V_{OUT}(I,K) \qquad (26)$$

$$T_M(I,K) = \frac{V_{MD}(I-1,K)\cdot T_M(I-1,K) + V_{OUT}(I,K)\cdot T_D(I,K)}{V_M(I,K)} \qquad (27)$$

From the relationship between the air temperature in zone (I) and that in zone (I+1) associated with the composite descending current temperature $T_M(I,K)$, we calculated the air volume $V_{IN}(I,K)$ entering zone (I) and the air volume $V_{MD}(0,K)$ going down along wall.

Table 3

	$V_{IN}(I,K)$	$V_{MD}(I,K)$
$T_M(I,K) \geq T(I)$	$=V_M(I,K)$	=0
$T(I) > T_M(I,K) > T(I+1)$	$=V_M(I,K)\cdot\dfrac{T_M(I,K)-T(I+1)}{T(I)-T(I+1)}$	$=V_M(I,K) - V_{IN}(I,K)$
$T_M(I,K) \leq T(I+1)$	=0	$=V_M(I,K)$

Heat transfer by temperature difference between vertical adjacent zones

The following equation is used to calculate heat flow, $q_B(I)$ from zone (I-1) to zone (I):

$$q_B(I) = C_B(I)\cdot A_B(I)\cdot[T(I-1)-T(I)] \qquad (28)$$

If $T(I-1) > T(I)$:

$$C_B(I) = 2.3W/(m^2\cdot{}^oC) \qquad (29)$$

If $T(I-1) < T(I)$, the mixture due to the density difference becomes active:

$$C_B(I) = 116W/(m^2\cdot{}^oC). \qquad (30)$$

The calculation procedure is the same as in the case of cooled surfaces when the surfaces are heated. But the calculation should start from the lowermost zone (N).

Air volume and heat balance in each zone

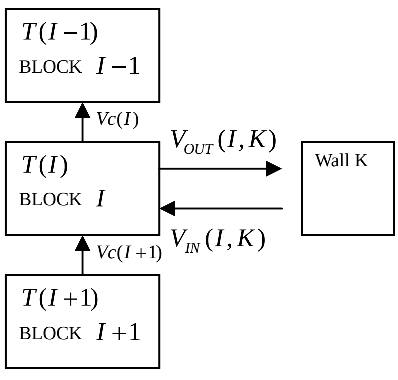

Figure 3 Air volume balance of zone(I)

The air volume balance in zone (I) is represented by the following equation:

$$\sum_{K=0}^{m}(V_{IN}(I,K)-V_{OUT}(I,K)) + V_C(I+1) - V_C(I) = 0 \qquad (31)$$

The heat balance equation in zone (I), except the uppermost zone (1) and the lowermost zone (N), is as follows:

$$\sum_{K=0}^{m} c\cdot\rho\cdot V_{IN}(I,K)[T_M(I,K)-T(I)]$$
$$+c\cdot\rho\cdot V_C(I+1)[T(I+1)-T(I)]$$
$$-c\cdot\rho\cdot V_C(I)[T(I-1)-T(I)] \qquad (32)$$
$$+C_B(I)\cdot A_B(I)\cdot[T(I-1)-T(I)]$$
$$+C_B(I+1)\cdot A_B(I+1)\cdot[T(I+1)-T(I)]$$
$$=c\cdot\rho\cdot V_a(I)\frac{dT(I)}{d\tau}$$

APPLICATIONS

The office building located in Beijing has five storeys, and each storey is 4m high. With a skylight on its top, an atrium is in the center of building and its size is 10m*10m*20m (high). There is an air conditioning system at the lower part of the atrium which is operated from 7:00 to 22:00. We create the model of the building in DeST, which is shown in Figure 4.

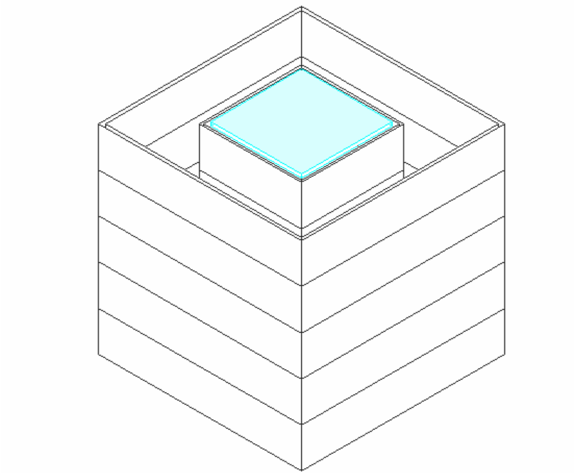

Figure 4 Building model in DeST

There are three kinds of skylight's material for the designer to select (see Table 4). We use the atrium modular of DeST to analysis this problem.

Table 4

material	**Heat transfer coefficient** $W/(m^2\cdot K)$	**shading coefficient** Sc
Double-layer glass	3.1	0.67
Low transmission low-e glass	2.1	0.49
High transmission Low-e glass	2.4	0.56

Heating/cooling load of atrium

The maximum heating/cooling load and the sum of the heating/cooling load in a year can be obtained after the dynamic simulation of thermal environment of the atrium, which are shown in Table 5. The heating and cooling load of low transmission low-e glass is the lowest one comparing with other two materials.

Although the Sc of high transmission low-e glass is greater than the low transmission low-e glass, but its heat transfer coefficient is smaller. In winter, high transmission low-e glass could get more solar radiation, however the building lost more heat through it. The effect of the heat transfer coefficient is greater than the Sc in winter, so the heating load of low transmission low-e glass is smaller. However, when it is in summer, the effect of the heat transfer coefficient is smaller than the Sc, so the cooling load of low transmission low-e glass is also smaller.

Comparing the cooling and the heating load, we find that the heating load is much smaller than the cooling load. It is because there is quite a lot of sunshine entering into the atrium.

Table 5

	Maximum heating load W/m^2	**sum of the heating load in a year** kWh/m^2	**Maximum cooling load** W/m^2	**sum of the cooling load in a year** kWh/m^2
Double-layer glass	50.2	6.6	140.2	63.8
Low transmission low-e glass	33.7	3.6	105.1	45.9
High transmission Low-e glass	38.7	4.1	119.1	53.4

Analysis of the thermal environment of typical days

- Typical days in winter (Jan.15th)

The load curve in Jan.15th is shown in Figure 6. When the HVAC system starts, there is a peak load. Along with the temperature getting higher and the solar radiation getting greater (shown in Figure 5), the heating load gets the minimum value at 16:00. And then the load start to increase until the HVAC system is closed.

Figure 7 shows the hourly vertical temperature distribution in the atrium using low transmission low-e glass. The differences of vertical temperature are quite small both in the day and night which is less than 1℃. The temperature decreases with the height from the floor level at night and the average temperature of atrium is lower than that during the day. In the daytime when it is from 14:00 to 18:00, the temperature of the area near the floor level is comparatively lower than the other cases.

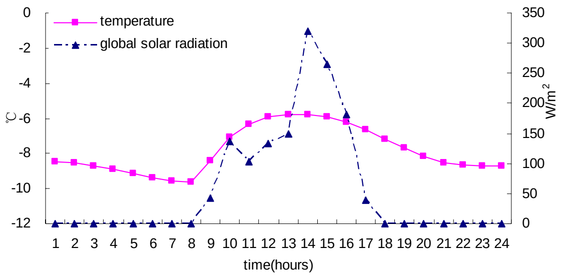

Figure 5 The outside temperature and global solar radiation in Jan. 15th

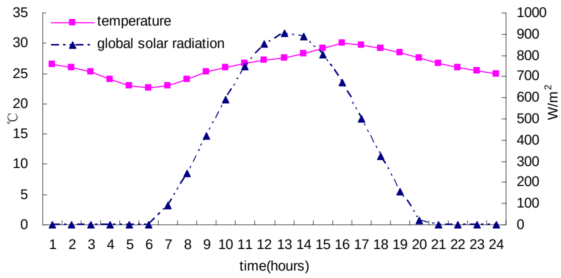

Figure 8 The outside temperature and global solar radiation in Aug. 16th

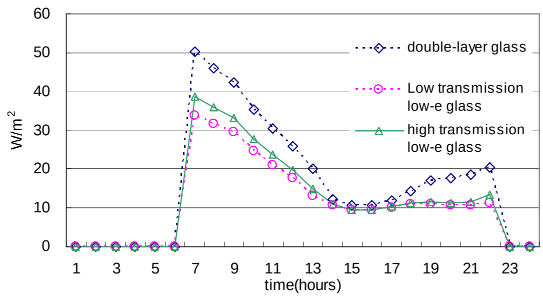

Figure 6 Hourly heating load in Jan. 15th

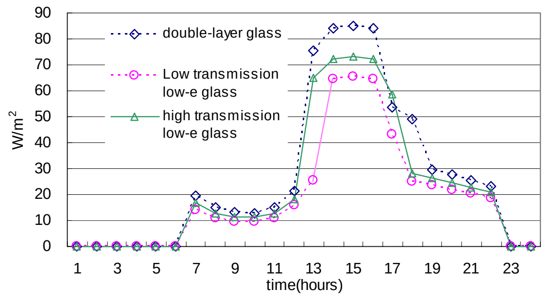

Figure 9 Hourly heating load in Aug. 16th

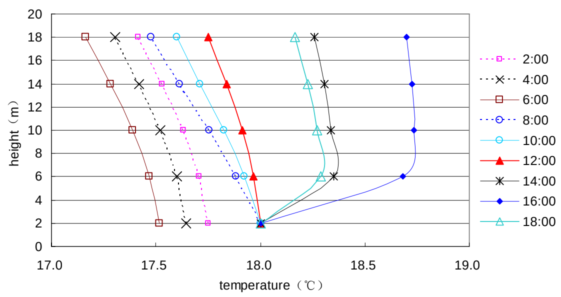

Figure 7 Vertical temperature distribution of the atrium in Jan. 15th （Low transmission low-e glass）

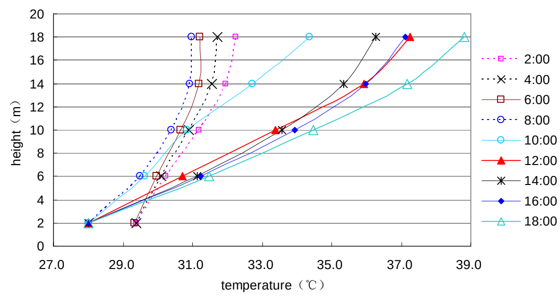

Figure 10 Vertical temperature distribution of the atrium in Aug. 16th （Low transmission low-e glass）

- Typical days in summer (Aug.16th)

The load curve in Aug.16th is shown in Figure 9. Along with the temperature getting higher and the solar radiation getting greater (shown in Figure 8), the cooling load gets the maximum value at 15:00. And then the load start to decrease until the HVAC system is closed.

Figure 10 shows the hourly vertical temperature distribution in the atrium of low transmission low-e glass. When it is at night, the temperature difference along the vertical axis is small which is from 1 to 2 ℃, but there is small temperature gradient. During the daytime, the temperature increases with the height from the floor level and the temperature greatest difference is about 11 ℃ when it is at 18:00.

CONCLUTIONS

The building design process of the atrium consists of several different stages. In different design stage, the key point of design and problems to be solved are different. We need to find the different method for each stage to simulate the annual thermal environment and energy consumption of the atriums.

This paper explains the simulation method in architecture design stage. And the authors add the dynamic simulation model of atrium into DeST (Designer's Simulation Toolkits), so that the annual dynamic simulation of atriums realized. The authors also apply this method to an atrium that is affected by transmitted solar radiation, and analysis the calculated results.

NOMENCLATURE

Solar radiation and longwave radiation

I_d = intensity of direct solar radiation got by exterior surface

I_{dn} = intensity of normal direct solar radiation

i = angle of incidence

S =area of surface

$Ratio$ = facular ratio

α = absorptive ratio

I_i = intensity of direct solar radiation got by inner surface

T_τ = transmission ratio

F_s, F_g, F_b = viewfactors of the exterior surface to the sky, ground surface and other buildings

$I_{s,s}$ =intensity of diffuse solar radiation from sky

I_{sh} =intensity of horizontal global solar radiation received by ground

I_b = intensity of average global solar radiation from adjacent buildings

$I_{j,window}$ ＝intensity of diffuse solar radiation which passes through the window

$F_{i,j}$ =viewfactor of the surface i to surface j

$B_{i,j}$ = absorption factor of the surface i to surface j

ε_j =emissivity

ρ_m = reflectivity

$C_{i,j}$ = radiative exchange areas

hr_{ij} =coefficient of heat transfer of longwave radiation

wall surface current model

I=zone number in an atrium

K=number of vertical wall

$T(I)$ =air temperature in zone(I)

$T_W(I,K)$ =inner surface temperature of vertical wall K

$q_W(I,K)$ =convective heat flow from wall K to zone(I)

$\alpha_C(I,K)$ =convective heat transfer coefficient

$c \cdot \gamma$ =product of specific heat of air and specific gravity weight

$V_{OUT}(I,K)$ =air volume flowing out of zone (I) toward the wall K

$T_D(I,K)$ =average temperature of the descending current generated in zone (I) on wall surface K.

$V_{IN}(I,K)$ =air volume into zone(I) from the surface current along the wall K

$V_{MD}(0,K)$ = air volume of the descending current moving down from zone(I) to zone(I+1) along the wall K

$V_M(I,K)$ = air volume of compound surface current

$T_M(I,K)$ =average temperature of compound surface current

$V_C(I)$ =air volume transferred from zone(I) to zone(I-1) through zone boundary

$C_B(I)$ =heat transfer factor by temperature difference between adjacent zones

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