STUDY ON ENERGY MODELING METHODS OF ATRIUM BUILDINGS

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ABSTRACT

In recent years, highly glazed atriums are favorable to architectural aesthetics and to taking advantage of daylighting and solar heating. However, the estimation of the building load of an atrium building is difficult because of the complex thermal phenomena occurred in the atrium space. The study aims to find out the methods of conducting accurate simulations of the cooling loads of various types of atriums, using whole building energy simulation tool – EnergyPlus. Cases of atrium buildings are collected and classified into various categories. For every category of atrium building, CFD models and energy models are developed. The simplified methods of simulating the cooling loads of atriums using different room air temperature patterns are summarised and applied to EnergyPlus. The non-dimensional height room air models with CFD results are defined as the baseline models to find out the most accurate model for every category of atrium building. In order to validate the methods an actual atrium office building is tested on site on a typical summer day and the results are compared with simulation results using the simplified methods. Finally, appropriate methods of simulating different types of atrium buildings are proposed.

INTRODUCTION

With the development of economy and technology, more new skyscrapers are built and even higher than the existing ones around the world. High-glazed atrium-type spaces are popularly employed in these high rise buildings, due to its architectural aesthetics as well as daylighting and solar heating advantages. Because of the complex thermal-airflow-coupled phenomena normally occurred in atrium spaces, conventional load calculation and system design procedures that relying on the assumption that zone air is thoroughly mixed –“well-stirred” zone model – might be inadequate to predict the thermal behaviour and to achieve good indoor environment and energy performance in these spaces (B. Griffith, Q. Chen 2004). The well-stirred zone model is well applied to typical forced air system where relatively good air mixing is the design intent, but might cause unacceptable calculation errors for such system designs or operating modes as displacement ventilation, underfloor air distribution, chilled ceiling, natural ventilation, mix-mode ventilation, large spaces e.g., atria, auditoria, and so on, where nonuniformity of zone air temperature is designed intently to improve energy efficiency and indoor air quality. It is of importance to consider the impact of nonuniform indoor air temperature on building load and energy use, which create a need for a different load calculation and system design method. Several researchers made efforts to find out a relatively accurate method for these particular spaces and systems. Griffith and Chen (2004) developed a framework and computer code for coupling detailed air models with building energy and load calculations and the heat balance model is reformulated to use zone air temperature as a variable defined separately for each surface, which can be applied for the energy modelling of spaces where the room air is stratified. Beausoleil-Morrison (2001) developed an adaptive controller to manage the interactions between the thermal and CFD modelling domains and implemented it within the ESP-r simulation program to support the conflation of CFD with dynamic whole building thermal simulation. Zhai et al (2001) described several different approaches to integrating energy simulation and CFD and proposed a staged coupling strategy for different programs. Djunaedy et al (2005) studied the implementation of external coupling between building energy simulation and CFD rather than a traditional internal coupling between the two different domains.

The particularity of the energy performance of the high-glazed large atrium due to its large size and high solar gains through the fenestration arises people's attention. Voeltzel et al. (2001) developed a new model (AIRGLAZE) to improve prediction of the thermal behaviour of highly-glazed atrium-type spaces. Laouadi et al. (1999) conducted a comparion study between simulation and field measurements of thermal parameters of an atrium building with skylight in Canada. Gan and Riffat (2004) employed CFD simulation to predict the air flow and temperature distribution in the atrium and compared the simulation results with the site measurement results, which show good compliance.

This paper studies on the buildings containing atriums with transparent glazing roof exposed to outdoor environment, which is the typical type of atrium building, to find out relatively accurate and practical load calculation methods for this type of buildings, using whole building energy simulation tool – EnergyPlus.

MODEL DEVELOPMENT OF ATRIUM BUILDINGS

Geometry models

The study focuses on the buildings with atrium in the centre, which opens to the adjacent spaces on each floor and enclosed by a transparent glazing roof to introduce daylighting into the atrium (Figure 1).

There are two points of concern when developing geometry models of atrium buildings:

1. The dimensions of the floor and height of atrium should be typical.
2. The ratio of floor area of atrium to main building should be appropriate and typical.

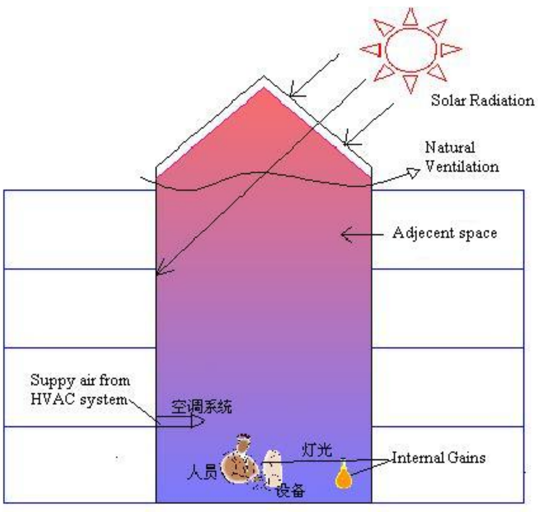


Figure 1 Schematic of atrium buildings with daylighting glazing roof

Table 1 Geometry models

MODEL	FLOOR AREA OF ATRIUM S(M^2)	HEIGHT OF ATRIUM H(M)	RATIO OF LENGTH TO WIDTH OF ATRIUM FLOOR	$h/\sqrt{S}$	FLOOR AREA OF MAIN BUILDING S'(M^2)
1		12	1	1.0	
2	144	40	1	3.3	1500
3		80	1	6.7	
4		12	2	1.0	
5	144	40	2	3.3	1500
6		80	2	6.7	
7		20	1	1.1	
8	324	40	1	2.2	3250
9		100	1	5.6	
10		20	2	1.1	
11	324	40	2	2.2	3250
12		100	2	5.6	

Referring to the statistics results of 30 existing atrium buildings conducted by Lei (2004) and the geometrical scale of an actual atrium office building located in Shanghai which is investigated by the authors, 12 geometry models are constructed for the study, as listed in Table 1. There are two sizes of the floor area – 144 sq.m. and 324 sq.m.; each size of atrium has two type of shape – square and rectangular with the ratio of length to width of 2; each size and each shape of atrium has three height, every 4 meters equals to 1 story. The dimensionless parameter $h/\sqrt{S}$ is introduced in this study to determine the height of the atrium. If the height is low enough, the air flow and temperature stratification in atrium space will be very similar to normal uniform spaces; if the height is high enough, e.g., $h/\sqrt{S}$ is more than 10, the influence of solar radiation through the glass roof to the occupancy zone in atrium will be very small and negligible. Considering most of the modern office buildings containing atrium spaces are high rise buildings, all the 12 models are with $h/\sqrt{S}$ equals to or more than 1. Moreover, the ratio of floor area of atrium to main building is set as 1:10 in the 12 models.

CFD Models

CFD models are developed with FLUENT6.3 to simulate the air flow and temperature stratification within the atrium space. Supposing that the adjacent zones on each floor are conditioned with the air temperature setpoints of 25^{o}C, the atrium surfaces near these zones is modelled as wall boundaries with a constant temperature. With the internal gains due to lighting, people and equipment the atrium floor is modelled as a wall boundary with a constant heat flux. Solar heat gain from the glass-glazed roof is relatively steady at a time, so the glass-glazed roof of the atrium is also modelled as a wall boundary with a constant heat flux, the value of which is obtained from the simulation with EnergyPlus energy models. The air is supplied through the inlet at the side wall near the bottom of the atrium and the exhausted through the outlet at the top of the atrium to take away heat accumulating under the glass-glazed roof. The temperature of supply air is set as 18 °C.

Energy Models

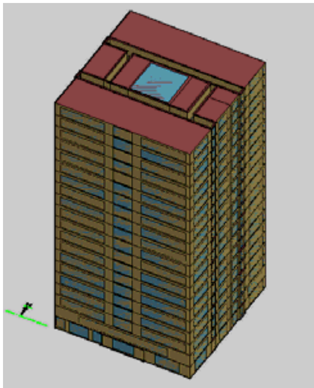


Figure 2 3-D view of energy model 2

The energy models are developed with EnergyPlus 3.0 and the specific module "Room Air Models" in the energy simulation program is used to account for the non-uniform temperature distribution in the air volume of atrium space. The room air models of EnergyPlus are coupled to the heat balance routines using the framework described by Griffith and Chen (2004), which is modified to include features needed for a comprehensive program for annual energy modelling rather than one for hourly load calculations and extended to allow exhaust air flows in addition to air system return flows (EnergyPlus 3.0 Manual 2008). EnergyPlus offers different types of room air models, including well-mixed, user defined, Mundt, UCSD displacement ventilation and so on. Among these models, the well-mixed model is set as the default for all zones; the user defined model containing user defined room air temperature and different room air temperature patterns can be used to study the atrium spaces. There are four room air temperature patterns: constant-gradient, two-gradient interpolation, non-dimensional height and surface mapping. The building models are constructed according to Table 1 and the atrium is located at the centre of the main building. Table 2 gives the input data of envelope and internal loads, with compliance to GB50189-2005. The window-to-wall ratio is 50%. International Weather for Energy Calculations (IWEC) of Shanghai is used in the simulation. Figure 2 shows the 3-D view of model 2. Since 14:00 p.m. is the typical peak load time of summer design day, all the simulations are conducted on this time.

Table 2 The input data of envelop components and internal loads

ENVELOPE				
External wall	U=1.0W/m^2.K			
Roof	U=0.7W/m^2.K			
Window	U=2.8W/m^2.K, SHGC=0.387			
Skylight	U=3.0W/m^2.K, SHGC=0.344, Interior shading in summer			
INTERNAL LOADS				
	LPD	EPD	People	Fresh air
Office	11W/m^2	20W/m^2	4m^2/person	30m^3/(h·p)
Lobby	11W/m^2	0W/m^2	20m^2/person	10m^3/(h·p)
Corridor	5W/m^2	0W/m^2	50m^2/person	0m^3/(h·p)

SIMPLIFIED MODELING METHODS

The temperature distributions in vertical direction in atrium obtained from CFD simulation are illustrated in Figures 3-6.

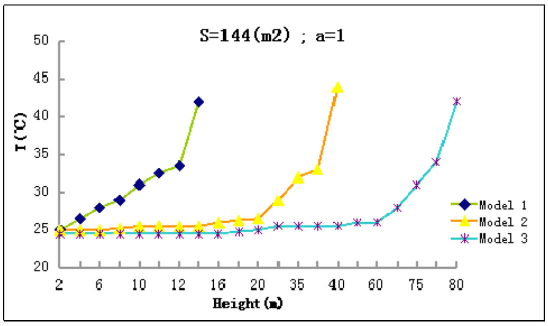


Figure 3 Temperature stratification in atrium at 14:00 of Model 1, 2, 3

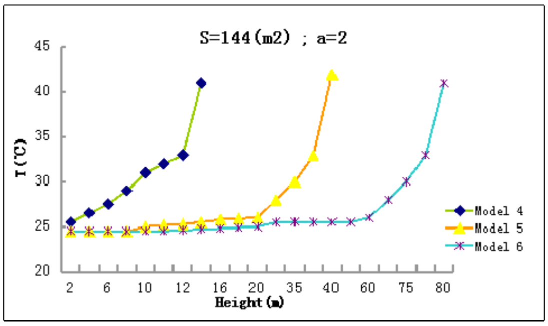


Figure 4 Temperature stratification in atrium at 14:00 of Model 4, 5, 6

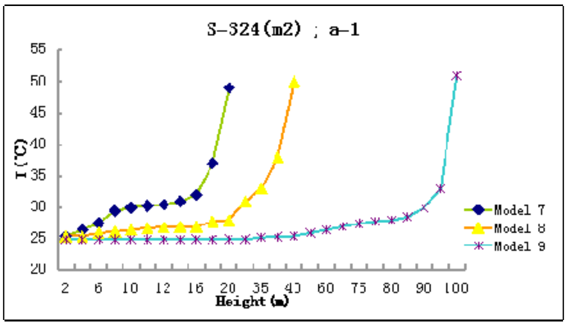


Figure 5 Temperature stratification in atrium at 14:00 of Model 7, 8, 9

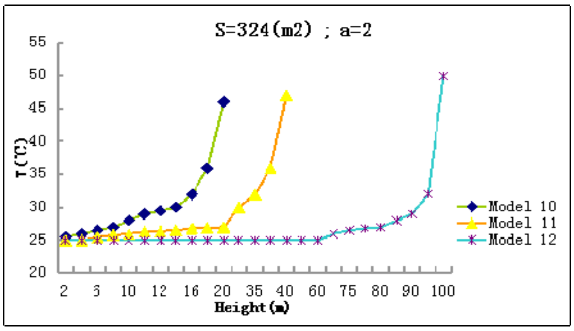


Figure 6 Temperature stratification in atrium at 14:00 of Model 10, 11, 12

The simulation results show that for the atrium spaces with the same floor area and the same shape of floor the atrium height has great impact on the vertical temperature distribution within the space. In general, the air temperature increases gradually along with the height and the temperature gradient becomes fairly large in the region near the top of the atrium. This is because the solar radiation goes through the glass roof and heats the internal surfaces to higher temperatures and then influences the air temperature through long-wave radiation between internal surfaces, convection between internal surface and room air etc. Due to the effect of buoyancy force, great amount of heat stays in the region near the top of atrium. The results show the air temperatures increase quickly in the region from roof down to 10m below the roof and the atriums with bigger floor area have higher air temperatures near the roof.

Therefore the atrium space can be divided into two sections vertically according to air temperature stratification:

1. From the floor surface to the plane surface 10m below the roof surface. In this region the air temperature varies little, generally from setpoint to 2°C higher than the setpoint, because the solar radiation has little effect in this region.
2. From the plane surface 10m below the roof surface to the roof surface. In this region the air temperature gradient is very big due to solar radiation effect.

The non-dimensional height room air temperature pattern in EnergyPlus is used to simulate the cooling loads of the atriums with the CFD simulation results of temperature distribution as the input data, which is regarded as the relatively accurate model and defined as the baseline model for the other simplified models to compare with. Three simplified modelling methods are proposed as described in Table 3.

Table 4 presents the simulation results of cooling loads at 14:00 pm of atrium of baseline model and mixing room air model (setpoint), which shows big errors of cooling loads calculated using mixing room air model compared to baseline model, meaning that the mixed room air model is not appropriate to large atrium space.

Table 4 Cooling load of atrium at 14:00 of mixing room air model (setpoint) and baseline model

MODEL	BASELINE MODEL (W)	MIXING ROOM AIR MODEL (SETPOINT) (W)	ERROR OF MIXING ROOM AIR MODEL TO BASELINE MODEL (%)
1	14366	27036	+88
2	14114	27664	+96
3	17079	31482	+84
4	13774	26632	+93
5	12212	26812	+120
6	15364	29870	+94
7	22544	63059	+180
8	19463	62879	+223
9	25828	72115	+179
10	20534	62177	+203
11	13710	61463	+348
12	22899	71549	+212

In order to avoid the effect of building area, cooling load per building area is used in later parts of paper. Table 5 gives the results of cooling loads calculating by three simplified methods and their errors compared to baseline model. The error of Simplified Method 1 quite big, meaning Simplified Method 1 is not applicable for the atriums; For model 1, 4, 7, 10, while using Simplified Method 2, the error of the results is under 10%; while using Simplified Method 3, the error of the results is between 14% and 30%; For model 2, 3, 5, 6, 8, 9, 11, 12, while using Simplified Method 2, the error of the results is great; while using Simplified Method 3, the error of the results is under 10%. Therefore it can be concluded that Simplified Method 2 is suitable for relatively lower atrium while Simplified Method 3 is suitable for relatively higher atrium.

GEOMETRICAL SCALE FACTOR

The cooling load of the atrium is influenced by the heat exchanges through the surfaces enclosing the atrium space, i.e., the roof surface exposed to the outdoor environment and side surfaces contacting the adjacent zone on each floor. Since the glass-glazed roof introduces the solar radiation, the larger the skylight area, the higher the cooling load; While the side surfaces are open to adjacent conditioned zones, the larger the side surface area the less the cooling load. Therefore, a geometrical scale factor R is introduced:

$$R = A / S = L \cdot h / S \qquad (1)$$

Where:

A= Total area of side surface of atrium

h= Atrium Height (m)

L= Perimeter of atrium floor (m)

S= Atrium floor area (m)

Table 6 gives the geometrical scale factor and the suitable simplified method proposed for each model.

Table 6 the geometry factor of the atriums and the suitable simplified method for each model

MODEL	R	SUITABLE SIMPLIFIED METHOD	ERROR TO BASELINE MODEL (%)
1	4.00	Constant gradient	-1.50
2	13.33	Non-dimensional	5.89
3	26.67	Non-dimensional	-3.28
4	4.25	Constant gradient	5.63
5	14.17	Non-dimensional	-6.86
6	28.33	Non-dimensional	7.02
7	4.44	Constant gradient	9.88
8	8.89	Non-dimensional	9.54
9	22.22	Non-dimensional	9.49
10	4.70	Constant gradient	8.99
11	9.41	Non-dimensional	9.42
12	23.52	Non-dimensional	7.13

For the atrium models with R less than 8, simplified method 2 – constant gradient room air model is proposed to calculate the cooling load of the atrium; while for those with R more than 8, simplified method 3 – non-dimensional height room air model can be used to calculate the cooling load of the atrium. The errors of the proposed simplified methods compared to baseline model are under 10%, which is acceptable.

VALIDATION OF THE METHODS BY SITE MEASUREMENT

To validate the accuracy of the simulation methods, an actual office building located at main campus of Tongji University was measured on a typical summer day (July 9, 2008) and the site measurement data is compared with the simulation results using different methods. The building has two stories underground and 21 stories above ground, with standard floor area of 2500 sq.m. The atrium is at the center of the main building and the floor is in square shape, with the side length of 15m. The roof of the atrium is made of glass and installed interior shading blinds. Table 7 lists the thermal performance parameters of the envelope components of the actual building, which are used as the input data of simulation.

Table 7 Envelope of actual building

COMPONENTS	U-VALUE (W/(M^2·K))	
Roof	0.62	
Exterior wall	0.73	
Window	2.5	SC =0.53(SHGC=0.46)
Skylight	2.5	SC =0.45(SHGC=0.384)

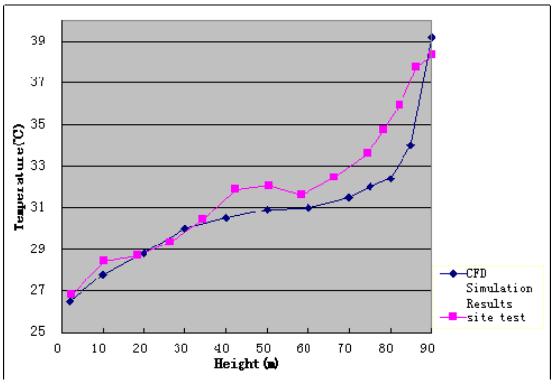


Figure 7 Temperature stratification in the atrium: CFD simulation vs. site measurement

The internal loads including lighting, equipment and people as well as their schedules are determined according to the actual data from site measurement. The infiltration rate of the perimeter zones are set as 0.2 h^{-1} and zero when the air conditioning system is operating. The real meteorological data collected from an automatic climate station is used as the weather data in both CFD simulation and energy simulation.

The temperature gradient in the atrium is tested on site by data loggers and CFD simulation is conducted, as illustrated in Figure 7. Figure 7 shows that in the region under the height of 40m, the CFD simulation results meet measured results well, while in the region higher than 40m, the CFD simulation results are smaller than the measured results. The air conditioning system on 11th floor to 17th floor of the building was not operating on the site measurement day, and the atrium has glass side walls exposed to outdoor from 18th floor to 21st floor, which causes temperature increasing on the side surfaces of the atrium and then higher air temperature on the same height than CFD simulation.

Table 8 gives actual and simulated cooling load of the entire building at 14:00 on July 9. The actual cooling load is calculated by multiplying the chilled water flow rate with the chilled water temperature difference. The actual temperature gradient in the atrium measured on site is used as the input data of the user defined room air model with non-dimensional height temperature pattern and the result of simulated cooling load is obtained. The simulated load meets quite well with the actual load, with the error of -4%.

Table 8 Cooling load of entire building: Actual vs. simulation

TIME	MEASURED LOAD (KW)	SIMULATED LOAD (KW)	ERROR (%)
14:00 July 9	1652	1581	-4

Table 9 presents the cooling loads of the atrium average by total building area calculated with different room air modeling methods. The geometry factor of the actual atrium building is 26.67. The mixing room air modeling method has very big error. The result of non-dimensional height room air model with CFD simulation result as the input meets the non-dimensional method with measured result as the input very well. The error of simplified method 2 (constant gradient) is less than that of simplified method 2 (non-dimensional height), which does not conform to the analysis done in above paper that simplified method 3 is the most suitable method among the three simplified methods for the atrium building with R of 26.67. To analyze the geometry models constructed in above paper further, the geometrical scale factor R in fact is the area ratio of side surfaces not exposed to outdoor to glass-glazed roof surface exposed to outdoor. Since the atrium in the actual building has not only glass-glazed roof but also glass-glazed side surfaces exposed to outdoor on four orientations, the equation of R should be reformulated by deducting the glass-glazed side surface area from the total side surface area A and adding it to the atrium floor area S. The reformulated R equals to 4.53, which is less than 8. For this building, simplified method 2 is more suitable than simplified method 3, conforming to the conclusions in above paper.

CONCLUSIONS

CFD models and energy models are developed and simplified modeling methods are summarized and validated by actual building data. Conclusions can be drawn from the study as followed:

1. The solar radiation through the glass-glazed roof has influence within the region from the roof surface to the plane surface 10m lower than the roof surface.
2. For highly glazed large atrium space in buildings, conventional mixing room air model with uniform air temperature equals to setpoint will cause very big errors for load and energy calculation.
3. User defined room air model with non-dimensional height temperature pattern using CFD simulation results of temperature gradient in atrium as the input can get fairly accurate load calculation results, which is also validated by actual building site measurement data.
4. 12 typical geometry models are constructed and three simplified energy modeling methods are proposed, i.e., mixing room air model with average air temperature, constant gradient room air model with two temperature node setting and non-dimensional room air model with three temperature node setting. Geometrical scale factor R is introduced as the judging factor of more accurate simplified energy modeling method. For atrium buildings with R less than 8, constant gradient room air model is more accurate, while for those with R more than 8, non-dimensional height room air model is more accurate.
5. For the atriums only with glass-glazed roof, R equals to the area ratio of total side surface to floor surface of the atrium; for the atriums

with both glass-glazed roof and side glass surfaces or only side glass surfaces, R equals the area ratio of total surface not exposed to outdoor to glass surface exposed to outdoor enclosing the atrium space.

REFERENCE

Griffith B., Chen Q. 2004. Framework for coupling room air models to Heat Balance Model Load and Energy Calculations. HVAC&R RESEARCH, Volume10, Number2.

Beausoleil-Morrison I. 2001. The adaptive coupling of computational fluid dynamics with whole-building thermal simulation. Building Simulation. Brazil.

Zhai Z., Chen Q., Klems J. H., Haves P. 2001. Strategies for coupling energy simulation and computational fluid dynamics programs. Building Simulation. Brazil.

Djunaedy E., Hensen J.L.M., Loomans M.G.L.C. 2005. External coupling between CFD and Energy Simulation: implementation and validation. ASHRAE Transactions, Vol. 111, Part 1.

Voeltzel, A., Carrié, F.R., Guarracino, G. 2001. Thermal and ventilation modelling of large highly-glazed spaces. Energy and Buildings. Vol 33.

Laouadi, A., Artif, M. R. 1999. Comparison between computed and field measured thermal parameters in an atrium building. Building and Environment. Vol. 34.

Gan G., Riffat S. B. 2004. CFD modelling of air flow and thermal performance of an atrium integrated with photovoltaics. Building and Environment, Vol. 39.

Lei T. 2004. Computer simulation research on ecological design strategies of atrium spaces, Master Thesis, Tsinghua University.

EnergyPlus3.0 Manual. 2008. Lawrence Berkeley National Laboratory, USA

GB50189-2005, China public building energy saving standard

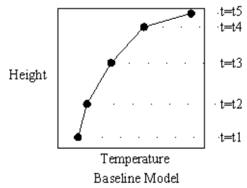
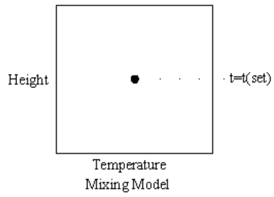
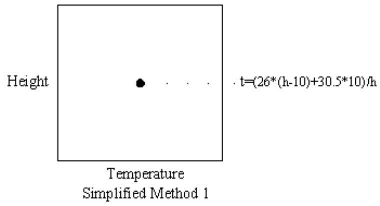
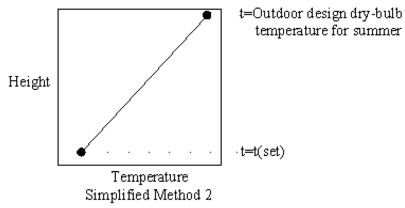
Table 5 Cooling load of the atrium per building area at14:00 calculated using different simplified methods and the errors of the simplified methods to baseline model

MODEL	BASELINE MODEL (W/M^2)	SIMPLIFIED METHOD 1 (W/M^2)	ERROR TO BASELINE MODEL (%)	SIMPLIFIED METHOD 2 (W/M^2)	ERROR TO BASELINE MODEL (%)	SIMPLIFIED METHOD 3 (W/M^2)	ERROR TO BASELINE MODEL (%)
1	3.76	3.06	-18.59	3.70	-1.50	3.18	-15.46
2	1.17	1.40	19.49	0.60	-48.75	1.24	5.89
3	0.72	0.88	22.54	0.31	-56.78	0.69	-3.28
4	3.60	2.71	-24.93	3.81	5.63	3.10	-13.94
5	1.01	0.86	-14.96	0.49	-51.44	0.94	-6.86
6	0.65	0.82	26.37	0.10	-85.06	0.69	7.02
7	1.61	1.87	15.99	1.77	9.88	2.08	29.07
8	0.71	0.86	20.30	0.20	-72.49	0.78	9.54
9	0.38	0.45	17.28	0.06	-83.07	0.42	9.49
10	1.47	1.69	15.22	1.60	8.99	1.89	29.02
11	0.50	0.62	23.62	0.17	-66.75	0.55	9.42
12	0.34	0.29	-14.06	0.11	-67.05	0.36	7.13

Table 9 Cooling load of atrium per building area calculated with of different modelling methods

NON-DIMENSIONAL HEIGHT ROOM AIR MODEL (MEASURED TEMPERATURE GRADIENT）(W/M^2)	MIXING ROOM AIR MODEL (SETPOINT) (W/M^2)	NON-DIMENSIONAL HEIGHT ROOM AIR MODEL (CFD SIMULATION RESULT) (W/M^2)	SIMPLIFIED METHOD 2: CONSTANT GRADIENT (W/M^2)	SIMPLIFIED METHOD 3: NON-DIMENSIONAL HEIGHT (W/M^2)
5.08	16.50	5.54	4.37	3.95
Error compared to Non-dimensional height room air model (measured temperature gradient) (%)		9.16	-13.80	-22.10

Table 3 Baseline model and simplified modeling methods

ROOM AIR MODELS	DETAILED DESCRIPTION	SCHEMATIC OF MODELS
Baseline Model	CFD simulation result of temperature gradient is used as the input data of non-dimensional height room air model.	
Mixing Room Air Model (setpoint)	This is the traditional calculation method and the atrium is considered as a fully mixed space with the uniform room air temperature equals to the setpoint (25°C).	
Simplified Method 1: Mixing Room Air Model (average temperature)	The room air temperature is defined as average air temperature (26*(h-10)+30.5*10)/h°C, which is calculated concerning the air temperature varies from 25°C to 27°C in the lower section and from 27°C to outdoor air dry-bulb design temperature (34°C) . This average temperature is also the setpoint of the atrium.	
Simplified Method 2: Constant Gradient Room Air Model	The air temperature is assumed as the setpoint of the atrium（25°C）at the height of 1.2m and as the outdoor dry-bulb design temperature (34°C) near the roof. The temperature gradient in the atrium is defined as (34-25)/(h-1.2) °C and is used as the input data of the constant gradient room air model in EnergyPlus.	
Simplified Method 3: Non-dimensional Height Room Air Model	The average air temperature in the atrium is defined as (26*(h-10)+30.5*10)/h°C and three temperature nodes are input into the non-dimensional height room air model. The first temperature node is at the height of 1.2m with temperature of the setpoint (25°C); the second node is at the height of 10m lower from the roof surface, with temperature of 25°C+2°C=27°C; the third node is near the roof, with temperature of 34°C (outdoor dry-bulb design temperature).