Energy and Buildings 42 (2010) 1654–1660

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Study on simulation methods of atrium building cooling load in hot and humid regions

Yiqun Pan [a,*], Yuming Li [a], Zhizhong Huang [a], Gang Wu [b]

[a] *Institute of Building Performance & Technology, Sino-German College of Applied Sciences, Tongji University, 1239 Siping Road, Shanghai 200092, China*
[b] *Weldtech Technology (Shanghai) Co. Ltd., China*

ARTICLE INFO

Article history:
Received 2 November 2009
Received in revised form 25 March 2010
Accepted 19 April 2010

Keywords:
Atrium building
Cooling load
Simulation
CFD model
Energy model

ABSTRACT

In recent years, highly glazed atria are popular because of their architectural aesthetics and advantage of introducing daylight into inside. However, cooling load estimation of such atrium buildings is difficult due to complex thermal phenomena that occur in the atrium space. The study aims to find out a simplified method of estimating cooling loads through simulations for various types of atria in hot and humid regions. Atrium buildings are divided into different types. For every type of atrium buildings, both CFD and energy models are developed. A standard method versus the simplified one is proposed to simulate cooling load of atria in EnergyPlus based on different room air temperature patterns as a result from CFD simulation. It incorporates CFD results as input into non-dimensional height room air models in EnergyPlus, and the simulation results are defined as a baseline model in order to compare with the results from the simplified method for every category of atrium buildings. In order to further validate the simplified method an actual atrium office building is tested on site in a typical summer day and measured results are compared with simulation results using the simplified methods. Finally, appropriate methods of simulating different types of atrium buildings are proposed.

1. Introduction

With development of economy and technology, an increasing number of new skyscrapers are built around the world. High-glazed atrium-type spaces are more and more designed in modern high rises because of their architectural aesthetics and daylight advantages. Because of complex thermal-airflow-coupled phenomena that normally occur in atrium spaces, conventional load calculation methods and system design procedures on the assumption that zone air is fully mixed – "well-stirred" zone model – might be inadequate to predict thermal behaviour, indoor environment, and energy performance in atrium spaces [1]. The well-stirred zone model is perfectly applied to mechanically forced air systems in which air mixing is fully achieved, but it may cause unacceptable errors for calculation of such systems 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. It further results in fresh thinking of traditional load calculation and system design. Several researchers made efforts to find out a relatively accurate method for these particular spaces and systems. Griffith and Chen [1] 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 [2] developed an adaptive controller to manage 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. [3] described several different approaches of integrating energy simulation and CFD, and proposed a staged coupling strategy for different programs. Djunaedy et al. [4] studied the implementation of external coupling between building energy simulation and CFD rather than a traditional internal coupling between the two different domains. Musy et al. [5] created zonal models for whole building air flow simulation and developed a tool named GenSPARK to automate the process of zonal model generation and simulation.

The unique energy performance of a high-glazed large atrium due to its large size and abundant solar heat gains through fenestration attracts people's attention. Voeltzel et al. [6] developed a new model (AIRGLAZE) to improve prediction of the thermal behaviour of highly glazed atrium-type spaces. Laouadi and Artif [7] conducted a comparison study between simulation and field

---

[*] Corresponding author. Tel.: +86 21 69584741; fax: +86 21 69589621.
E-mail address: yiqunpan@mail.tongji.edu.cn (Y. Pan).

0378-7788/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.enbuild.2010.04.008

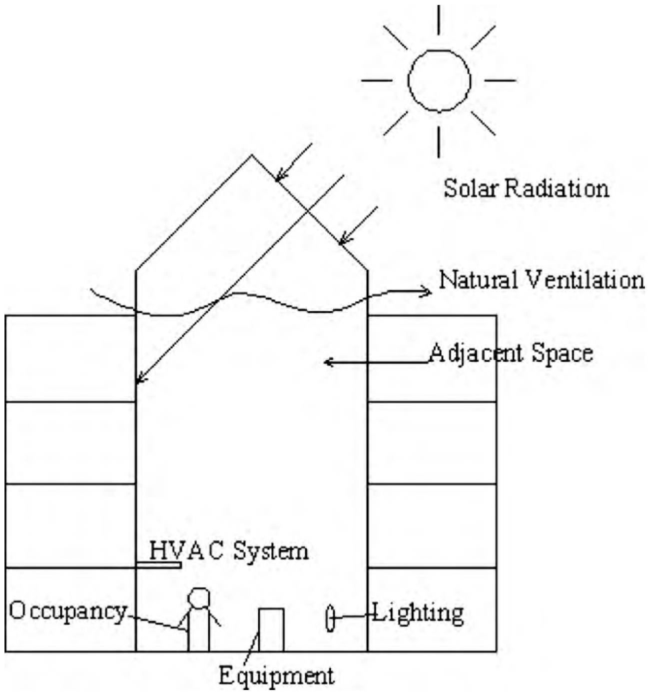


Fig. 1. Schematic of atrium buildings with daylight glazing roof.

measurements of thermal parameters of an atrium building with skylight in Canada. Gan and Riffat [8] employed CFD simulation to predict air flow and temperature distribution in an atrium and compared the simulation results with the site measurement results, which show good compliance. Wang et al. [9] proposed a mathematical model for large space buildings to predict the vertical temperature distribution of hybrid ventilation. Aldawoud and Clark [10] investigated the energy performance of a central atrium and compared it with that of a courtyard with the same geometric proportions. This paper presents relevant study on buildings in hot and humid regions that contain large atrium spaces with transparent glazing roof exposed to outdoor environment. It attempts to work out accurate and practical load calculation methods for typical type of atrium buildings by using whole building energy simulation tool – EnergyPlus.

2. Model development of atrium buildings

2.1. Geometry models

The study focuses on buildings with an atrium in the centre. It has opens to the adjacent spaces on each floor and has a transparent glazing roof to introduce daylighting into the atrium (Fig. 1).

There are two considerations when developing geometry models of atrium buildings:

(1) Floor dimension and atrium height shall be typical.
(2) Ratio of floor area of atrium to main building shall be appropriate and typical.

Referring to statistics results of 30 existing atrium buildings conducted by Lei [11] and the geometrical scale of an actual atrium office building investigated by the authors in Shanghai, 12 geometry models are constructed for the study, as listed in Table 1. There are two sizes of the floor area – 144 m^2 and 324 m^2; each size of atrium has two types of shape – square and rectangular with the ratio of length to width of 2; each size and each shape of atrium has three heights, every 4 m equals to 1 story. A dimensionless factor – $h/\sqrt{S}$ is introduced to specify the geometrical shape of atria, where, h is the height and S is the floor area of an atrium respectively. If the height is small enough, the air flow and temperature stratification in atrium space will be very similar to normal uniform spaces; if the height is big 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 $h/\sqrt{S}$ equal 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.

2.2. CFD models

CFD models are developed with FLUENT6.3 to simulate air flow and temperature stratification in atrium space. Supposing that adjacent zones on each floor are conditioned with temperature setpoints of 25 °C, the atrium surfaces near these zones are 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. For a specific short moment, solar radiant heat gain from the glass roof is steady, so the glass roof is also modelled as a wall boundary with a constant heat flux, and its value is obtained from EnergyPlus simulation. Simulations are only conducted with CFD and EnergyPlus models on 2 pm when the peak cooling load occurs. The cooling load is simulated with medium thermal mass for the building model, and it is validated by the on site measurement results of an actual building described in the later part of this paper. The site measurement shows that both the outdoor air temperature and the atrium space cooling load reach their peak value at 2 pm The air is supplied through the inlet on the side wall near the bottom of the atrium and part of return air is exhausted outside. There are also two outlets at the top of the atrium to take away heat accumulated under

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	144	12	1	1.0	1500
2		40	1	3.3	
3		80	1	6.7	
4	144	12	2	1.0	1500
5		40	2	3.3	
6		80	2	6.7	
7	324	20	1	1.1	3250
8		40	1	2.2	
9		100	1	5.6	
10	324	20	2	1.1	3250
11		40	2	2.2	
12		100	2	5.6	

Table 2
The input data of envelop components and internal loads.

Envelope				
External wall	$U = 1.0\,\mathrm{W/m^2\,K}$			
Roof	$U = 0.7\,\mathrm{W/m^2\,K}$			
Window	$\mathrm{U = 2.8\,W/m^2\,K}$, SHGC = 0.387			
Skylight	$\mathrm{U = 3.0\,W/m^2\,K}$, SHGC = 0.344, interior shading in summer			
Internal loads	LPD	EPD	People	Fresh air
Office	$11\,\mathrm{W/m^2}$	$20\,\mathrm{W/m^2}$	$4\,\mathrm{m^2}$/person	$30\,\mathrm{m^3/(h\,p)}$
Lobby	$11\,\mathrm{W/m^2}$	$0\,\mathrm{W/m^2}$	$20\,\mathrm{m^2}$/person	$10\,\mathrm{m^3/(h\,p)}$
Corridor	$5\,\mathrm{W/m^2}$	$0\,\mathrm{W/m^2}$	$50\,\mathrm{m^2}$/person	$0\,\mathrm{m^3/(h\,p)}$

the glass roof. While the indoor temperature set point is 25 °C, the supply air temperature is set at 18 °C. The supply air is also dehumidified by the cooling coils to maintain acceptable humidity in the atrium.

2.3. Energy models

The energy models are developed with EnergyPlus 3.0 and the specific module “Room Air Models” in the program is used to simulate the nonuniform air temperature distribution in the atrium space. The room air models of EnergyPlus are coupled with the heat balance routines using the framework described by Griffith and Chen [1]. The room air model is modified to include features needed for a comprehensive program for annual energy modelling rather than for hourly load calculations, and it is extended to allow exhaust air flows in addition to air system return flows [12]. EnergyPlus offers different types of room air models, including those for well-mixed, user-defined, Mundt, UCSD displacement ventilation and so on. Among those models, the well-mixed model is set as the default for all zones; the user-defined model based on user-defined room air temperature and its different 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 at the centre of the main building. Table 2 gives the input data of building envelope and internal loads in compliance with GB50189-2005 [13]. The window-to-wall ratio is 50%. International Weather for Energy Calculations (IWEC) of Shanghai is used in the simulation. Fig. 2 shows the 3-D view of Model 2.

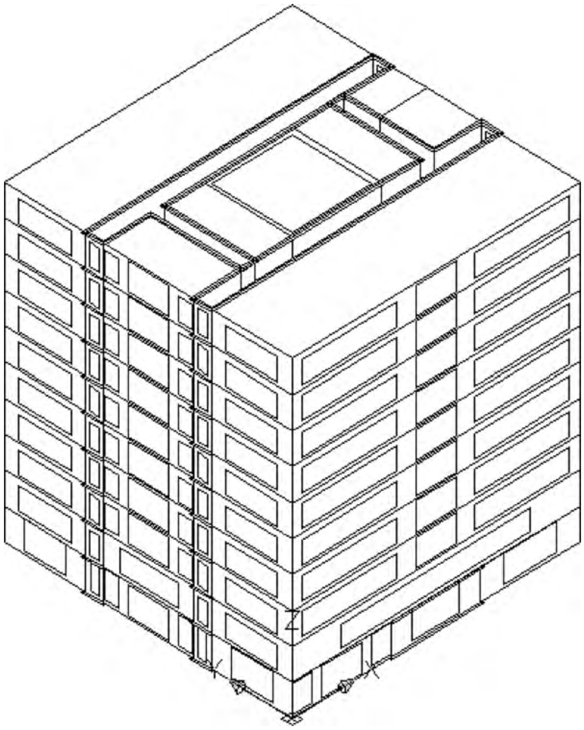


Fig. 2. 3-D view of energy Model 2.

3. Simplified modelling methods

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

The simulation results show that for 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 solar radiation going through the glass roof increases internal surfaces temperatures and influences air temperature via long-wave radiation between internal surfaces, convection between internal surface and room air and etc. Due to effect of buoyancy force, a great amount of heat accumulates and stays near the top of atrium. The results show the air temperature increases quickly from roof down to 10 m below the roof and the greater glazing areas of atria roof the 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 to the plane 10 m below the roof. Within this region the air temperature varies little, generally ranging from indoor set point to 2 °C above the set point, because solar radiation impacts little on this region.

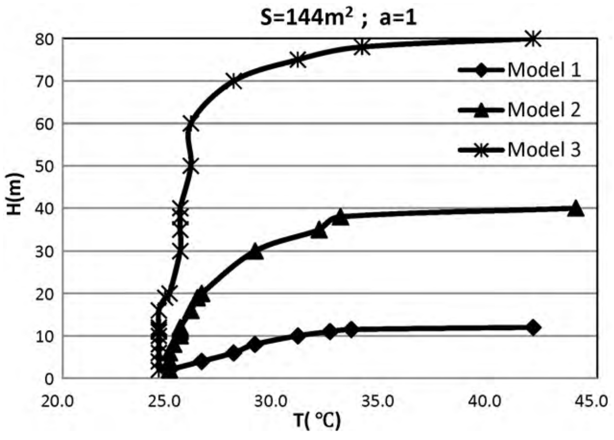


Fig. 3. Temperature stratification in atrium at 2 pm of Model 1, 2, 3.

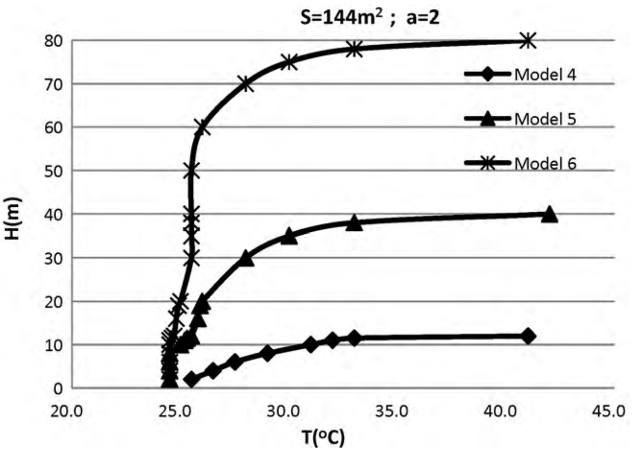


Fig. 4. Temperature stratification in atrium at 2 pm of Model 4, 5, 6.

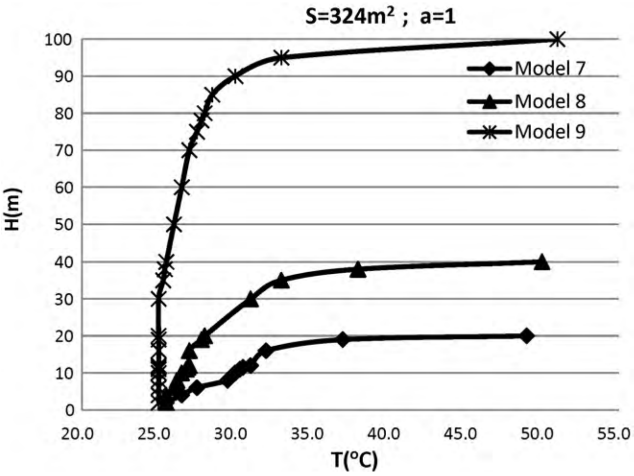


Fig. 5. Temperature stratification in atrium at 2 pm of Model 7, 8, 9.

(2) From the plane 10 m below the roof to the roof surface. Within this region the air temperature gradient is significantly big due to the strong solar radiation.

Such division of atrium space is not applicable to Model 1 and Model 4, which limit the atrium height within 12 m.

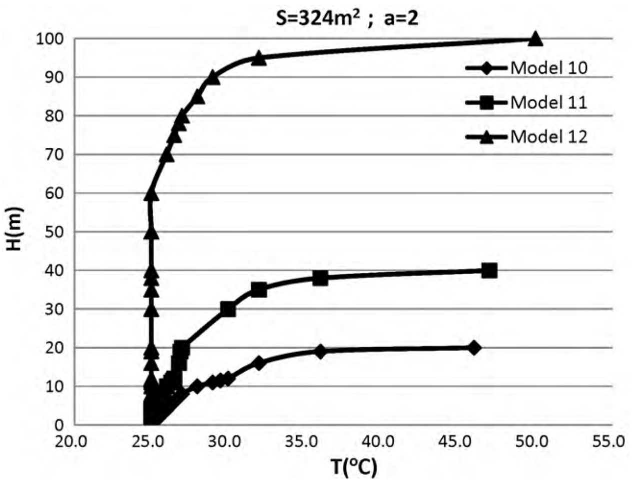


Fig. 6. Temperature stratification in atrium at 2 pm of Model 10, 11, 12.

Based on above analysis, three simplified modelling methods are proposed: Simplified Model 1 – mixed room air model (set point), Simplified Model 2 – constant gradient room air model and Simplified Model 3 – non-dimensional height room air model. Table 3 gives the definition and description of the three simplified modelling methods, the baseline model, and the mixed room air model. The non-dimensional height room air temperature pattern in EnergyPlus is used to simulate cooling load of atria with CFD simulation results of temperature distribution as input data. This method creates the baseline model, which is supposed to be relatively accurate for the other models to compare with.

Table 4 presents the simulation results of cooling loads at 2 pm of the atrium baseline model and the mixing room air model (set point). Significant errors between the mixing room air model and the baseline model conclude that the mixed room air model is not appropriate for cooling load calculation of large atrium spaces.

In order to reduce floor area's impact on the building models, cooling load per floor area is used in the later analysis. Floor area refers to the total area of a building. Table 5 gives the results of cooling loads per floor area calculated by three simplified methods and their respective errors compared to the baseline model. Errors between the Simplified Method 1 and the baseline model are significant. If Simplified Method 2 is applied to Model 1, 4, 7, 10, errors are less than 10%; and if Simplified Method 3 is applied, errors are between 14% and 30%. If Simplified Method 2 is applied to them Model 2, 3, 5, 6, 8, 9, 11, 12, errors are great; and if Simplified Method 3 is applied to them, errors are less than 10%. According to Table 1, $h/\sqrt{S}$ of Model 1, 4, 7, 10 is 1–1.1, referring to relatively lower atrium; $h/\sqrt{S}$ of models 2, 3, 5, 6, 8, 9, 11, 12 is 2.2–6.7, referring to higher atrium. Therefore it can be concluded that Simplified Method 2 is suitable for low atrium while Simplified Method 3 is suitable for high atrium.

4. Geometrical scale factor

Atrium cooling load is influenced by heat transfer through surfaces surrounding the atrium space, i.e., the roof surface exposed to the outdoor environment and side surfaces contacting the adjacent zone on each floor. Since glass roof introduces solar radiation into the inside, the larger the skylight area the higher the cooling load is supposed to be; When side surfaces are open to adjacent conditioned zones, the larger the side surface area the less the cooling load is supposed to be. Therefore, another geometrical scale factor R – the ratio of total side surface area to floor area of an atrium, is introduced to determine which simplified method is the most accurate for different geometry.

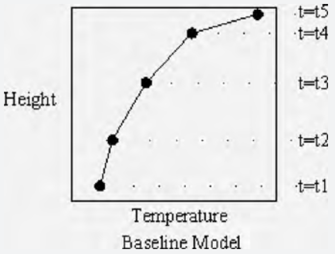
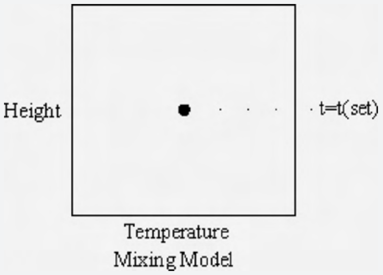
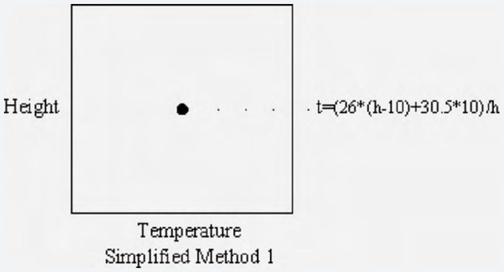
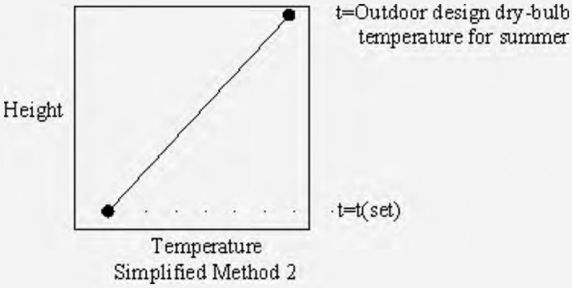
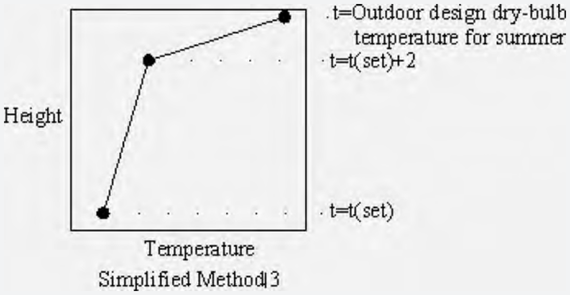
$$R = \frac{A}{S} = L \cdot \frac{h}{S} \qquad (1)$$

where A is the total area of side surface of atrium (m^2); h is the atrium height (m); L is the perimeter of atrium floor (m); S is the atrium floor area (m^2).

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

For atrium models with R less than 8, Simplified Method 2 – constant gradient room air model is proposed to calculate atrium cooling load; while for those with R more than 8, Simplified Method 3 – non-dimensional height room air model can be used to calculate atrium cooling load. Errors between the proposed simplified methods and the baseline model are all less than 10%, which is acceptable for engineering calculation.

Table 3
Baseline model and simplified modelling 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 $(26 \times (h-10)+30.5 \times 10)/h$ °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 1.2 m 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 $(26 \times (h-10)+30.5 \times 10)/h$ °C and three temperature nodes are input into the non-dimensional height room air model. The first temperature node is at the height of 1.2 m with temperature of the setpoint (25 °C); the second node is at the height of 10 m 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)	

5. Validation of the methods by site measurement

To validate the accuracy of the simulation methods, an actual office building in main campus of Tongji University was measured on a typical summer day (July 9, 2008) and the site measurement data are 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 m^2. The atrium is at the centre of the building and its floor is of square shape by 15 m × 15 m. The glass roof is installed with interior shading blinds.

Table 4
Cooling load of atrium at 2 pm 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	14,366	27,036	+88
2	14,114	27,664	+96
3	17,079	31,482	+84
4	13,774	26,632	+93
5	12,212	26,812	+120
6	15,364	29,870	+94
7	22,544	63,059	+180
8	19,463	62,879	+223
9	25,828	72,115	+179
10	20,534	62,177	+203
11	13,710	61,463	+348
12	22,899	71,549	+212

Table 5
Cooling load of the atrium per building floor area at 2 pm 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 6
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

Table 7 lists thermal parameters of the building envelope as the input data of simulation.

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

The temperature gradient in the atrium is measured and recorded in data loggers, and CFD simulation is conducted, as illustrated in Fig. 7. Fig. 7 shows that from the atrium floor to the height of 40 m, the CFD simulation results meet measured results well, while from 40 m height to the atrium roof, the CFD results are smaller than the measured ones. The discrepancy is due to the fact that the air conditioning system from 11th to 17th floor was not operating when site measurement was taken, and the atrium has glass facade exposed to outdoor between 18th and 21st floor that causes temperature increase on the atrium side surfaces.

The actual cooling load of the entire building at 2 pm on July 9 is 1652 kW, which is calculated by multiplying chilled water flow rate with chilled water delta *T*. The actual temperature gradient in the atrium measured on site is used as the input to the user-defined room air model with non-dimensional height temperature pattern and the resulted cooling load from simulation is 1581 kW at 2 pm on July 9. The simulated load matches quite well with the actual load, with the error of −4%.

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)

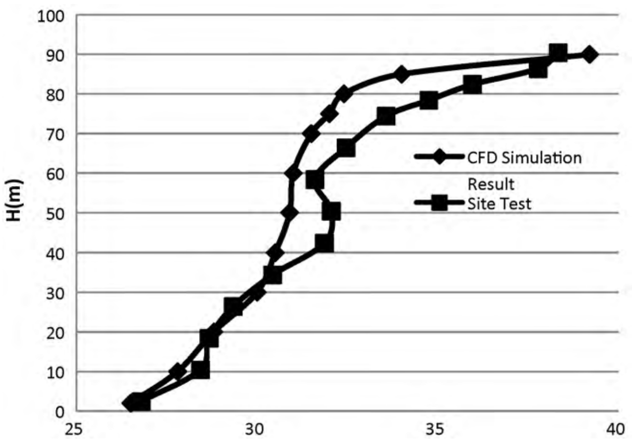


Fig. 7. Temperature stratification in the atrium: CFD simulation versus site measurement.

Table 8
Cooling load of atrium per building floor area calculated with 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 8 presents the atrium cooling loads resulted from different room air modelling methods and divided by total building floor areas. The geometry factor of the actual atrium building is 26.67. The mixing room air modelling method has significant errors. The result of non-dimensional height room air model with CFD simulation as the input matches the non-dimensional method with measured data as the input very well. The error of Simplified Method 2 (constant gradient) is less than that of Simplified Method 3 (non-dimensional height). This result does not conform to the above conclusion that Simplified Method 3 is the most suitable method among the three simplified methods for the atrium building with *R* of 26.67. To further analyze the above geometry models, the geometrical scale factor *R* in fact is the ratio of side surfaces area not exposed to the outdoor to glass roof surface area exposed to the outdoor. Since the atrium in the actual building has not only glass roof but also glass side surfaces exposed to outdoor on four orientations of facades, the equation of *R* should be reformulated by deducting the glass side surface area from the total side surface area *A* and adding it to the atrium floor area *S*. After the adjustment, we get the reformulated *R* equal to 4.53 and less than 8. Using this reformulated *R* as the determining factor, Simplified Method 2 is more suitable than Simplified Method 3. This conforms to the conclusion above.

6. Conclusions

CFD and energy models are developed, and simplified modelling methods are proposed and validated by measured data in an actual atrium. Conclusions can be drawn from the study as follows:

(1) For tall buildings with moderately sized atria, solar radiation through glass roofs has impact from the roof to the plane 10 m below the roof.

(2) For highly glazed large atrium space in buildings, conventional mixing room air model with uniform air temperature equal to indoor set point will cause significant errors for load and energy calculation.

(3) User-defined room air model with non-dimensional height temperature pattern using simulated temperature gradient in CFD as input can get fairly accurate load calculation results, which is also validated by actual site measurement.

(4) 12 typical geometry models are constructed and three simplified energy modelling methods are proposed. They include 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, etc. Geometrical scale factor *R* is introduced as the determining factor of more accurate simplified energy modelling method. For atrium buildings with *R* less than 8, the constant gradient room air model is more accurate, while for those with *R* more than 8, the non-dimensional height room air model is more accurate.

(5) For the atria only with glass roof, *R* shall be defined as the ratio of total side surface area to floor surface area of an atrium; for atria with both glass roof and side glass surfaces or only side glass surfaces, *R* shall be defined as the ratio of total surface area not exposed to the outdoor to glass surface area exposed to outdoor surrounding atrium spaces.

(6) It is necessary to make the simplified methods to be practical for HVAC designers and engineers. Further research will examine simulation results of the simplified models under part load conditions and how the simulation is executed when they are incorporated into transient energy consumption models (e.g., full-year runs of EnergyPlus).

References

[1] B. Griffith, Q. Chen, Framework for coupling room air models to Heat Balance Model Load and Energy Calculations, HVAC&R Research 10 (2) (2004).
[2] I. Beausoleil-Morrison, The Adaptive Coupling of Computational Fluid Dynamics with Whole-building Thermal Simulation, Building Simulation, Brazil, 2001.
[3] Z. Zhai, Q. Chen, J.H. Klems, P. Haves, Strategies for Coupling Energy Simulation and Computational Fluid Dynamics Programs, Building Simulation, Brazil, 2001.
[4] E. Djunaedy, J.L.M. Hensen, M.G.L.C. Loomans, External coupling between CFD and Energy Simulation: implementation and validation, ASHRAE Transactions 111 (2005) (Part 1).
[5] M. Musy, F. Winkelmann, E. Wurtz, A. Sergent, Automatically generated zonal models for building air flow simulation: principles and applications, Building and Environment 37 (2002) 873–881.
[6] A. Voeltzel, F.R. Carrié, G. Guarracino, Thermal and ventilation modelling of large highly glazed spaces, Energy and Buildings 33 (2001).
[7] A. Laouadi, M.R. Artif, Comparison between computed and field measured thermal parameters in an atrium building, Building and Environment 34 (1999).
[8] G. Gan, S.B. Riffat, CFD modelling of air flow and thermal performance of an atrium integrated with photovoltaics, Building and Environment 39 (2004).
[9] X. Wang, C. Huang, W. Cao, Mathematical modeling and experimental study on vertical temperature distribution of hybrid ventilation in an atrium building, Energy and buildings 41 (2009) 907–914.
[10] A. Aldawoud, R. Clark, Comparative analysis of energy performance between courtyard and atrium in buildings, Energy and buildings 40 (2008) 209–214.
[11] T. Lei, Computer simulation research on ecological design strategies of atrium spaces, Master Thesis, Tsinghua University, 2004.
[12] EnergyPlus3.0 Manual, Lawrence Berkeley National Laboratory, USA, 2008.
[13] GB50189-2005, China public building energy saving standard.