CFD AND DAYLIGHT SIMULATION CALIBRATED WITH SITE MEASUREMENT FOR WAITING HALL OF SHANGHAI SOUTH RAILWAY STATION

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ABSTRACT

The Shanghai South Railway Station, which connects urban subways and inter-city railways, is one of the largest transportation hubs in Shanghai and East China. This paper presents study on indoor environment, bascally consisting of temperature distribution and daylight performance, of the waiting hall of the Station through the combination of computer simulation and on-site measurement. The waiting hall is 30 m high and roofed with transparent glass. In order to analyze its vertical thermal stratification, daylight performance and its positive and negative effects, CFD and daylight computer simulation as well as on-site measurement for temperature stratification and daylight illuminance were conducted. Simulation results have been compared with measured data and reasons that account for the difference been analyzed too. The prediction for the vertical temperature stratification has been validated for further design guidelines of highly-glazed atrium-type spaces.

INTRODUCTION

The 56,000 m^2 Shanghai South Railway Station, has started its operation since July 2006 (See Figure 1). The main building – the waiting hall – is of a 270-meter diameter and 42.5-meter high cylinder, which contains a 220-meter diameter and 30-meter high internal hall at 7.5 meter elevation and a circling-around perimeter hall at 9.9-meter elevation . The entire roof and façade of the building is mainly composed of transparent glass. The roof consists of three layers from outmost to inmost: duralumin shading blinds around the 35m radius circle, polycarbonate glass, and porous sound absorption board. The façade is composed of double-pane clear glass. Although the glass roof and walls are capable of introducing abundant daylight into interior spaces such that electricity use of artificial lighting may be significantly reduced, the increase in space cooling load and potential thermal discomfort due to solar radiation has triggered substantial dispute not only in the building industry but in the public in Shanghai. In order to save energy use of air-conditioning systems, conditioned air is supplied at 4-meter height of the 30-meter high space to just provide thermal comfort to occupied spaces typically below 2.5 meter.

Figure 1 Bird's eye view of Shanghai South Railway Station

Although large highly-glazed atrium-type spaces are favorable to architectural aesthetics and to taking advantage of daylighting andsolar heating, their thermal behaviour remains difficult to be predicted. Because of complex thermal-airflow-coupled phenomena, computer simulation and site measurement rather than simple calculation must be employed to assess thermal, daylight, and energy performance of such atrium-type spaces. Bryn (1995) discussed atrium buildings from the perspective of their functions, thermal comfort, visual impression, indoor air quality, and energy efficiency, etc. Morover, the author gave an overview of the status and limitation of simulation tools to study phenomenon in atrium buildings. Voeltzel et al. (2001) developed a new model (AIRGLAZE) to improve prediction of the thermal behaviour of highly-glazed atrium-type spaces. The new model consists of an envelope module to calculate conductive and radiative heat transfer in the building envelope, and it is coupled with a zonal airflow model to predict air movement within the room. Laouadi et al. (1999) conducted a comparion study between simulation and field measurements of thermal parameters of an atrium building with skylight in Canada. The temperature stratification and solar radiation entering the atrium through skylights are predicted by simulation and measured in winter and summer. Comparion results show better agreement on solar radiation than air termperature. Goecer et al. (2006) introduced a performance-based model for energy use and user-comfort evalulation of atrium buildings with the use of multiple building simulation tools such as WINDOW, EnergyPlus, COMIS, Delight, Fluent, etc. Aldawoud et al. (2008) did a comparative research on energy performance between an atrium and a courtyard with the same geometric proportions using DOE2.1e for modeling. Galasiu et al. (2002) used field-measured data to investigate applicability and accuracy of Adeline software in simulating illuminance distribution from daylighting and electrical lighting in an atrium building. Calcagni et al. (2004) developed a simplified method to predict daylight factor in atrium buildngs through computer simulation using Radiance.

This paper presents comparative analysis between CFD and daylight simulation and site measurement on thermal and daylight performance of the highly-glazed waiting hall of Shanghai South Railway Station. Some of the site measurement data such as outdoor air temperatures, solar radiation, supply air temperatures and velocities are used as input data of simulation models, the others are compared with the simulation results for calibration.

SITE MEASUREMENT

Due to its huge volume of passengers in summer, it is not possible to conduct long term measurement in real operation of such a transportation hub as Shanghai South Railway Station. Compromsingly, site measurement was conducted for the waiting hall for continuous 48 hours during typical summer period of Shanghai – from July 27^{th} to 28^{th}, 2007. Parameters measured include weather data, indoor temperature distribution and stratification, lighting illuminance distribution, supply air temperature and velocity, and etc.

Measurement instruments and methods

A mobile automatic weather monitoring and recording station was installed on the roof of an auxiliary building close to the main building to monitor and record weather data, including outdoor air dry bulb temperature and humidity, wind velocity and direction, solar radiation, etc. Automatic temperature sensors and data loggers were fastened to ropes below helium gas balloons at different height to measure the vertical distribution of indoor air temperature. There were 12 horizontal measuring points and 4 heights vertically at each point (1.5m, 5m, 15m and 30m from floor) in the 7.5m elevation internal hall, and 9 horizontal measuring points and 2 heights vertically at each point (5m and 12m from the floor) in the 9.9m elevation perimeter hall. Figure 2 maps all of the temperature measuring points. Figure 3 is a picture taken inside the waiting hall where red helium gas balloons floated during measuring period.

Hand illuminance meters were used to measure daylight illuminance, and supply air temperature and velocity on different positions. Figure 4 maps all of the daylight measuring positions.

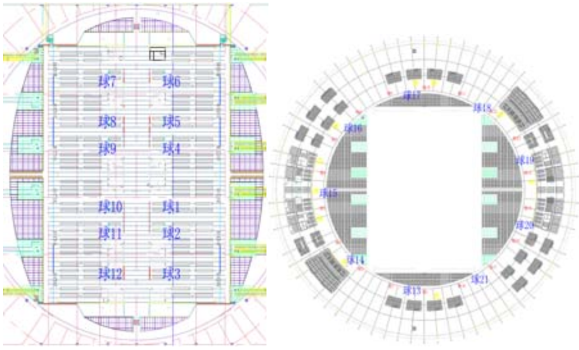


Figure 2 Measuring points of balloons in 7.5m elevation internal hall and 9.9m elevation perimeter hall

Figure 3 Picture taken inside the waiting hall during measuring period

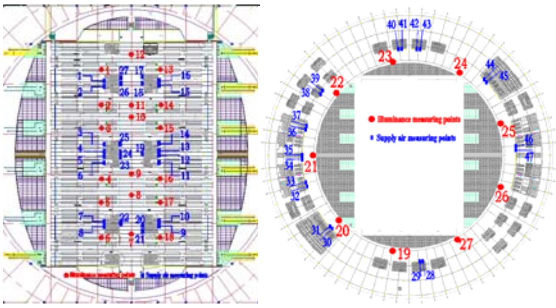


Figure 4 Measuring points of illuminance, and supply air temperature and velocity in 7.5m elevation internal hall and 9.9m elevation perimeter hall

Measurement results

Weather

It was cloudy on July 27th 2007.

- ✧ Air temperature: minimum 25.9°C; maximum 36.8°C; average 30.2°C
- ✧ Relative humidity: minimum 55%; maximum 87%;
- ✧ Total solar radiation: peak 622W/m^2.

Illuminance distribution

Illuminance was measured without artificial lighting to study the effect of daylighting. The measured data was recorded every one hour from 9:00am to 4:00pm. Table 1 presents the measurement results. It began raining at 4:00pm, therefore the illuminance decreased dramatically from then. Table 1 shows that measured illuminance values are much higher than those required by design standard during most of the daytime even when all of artificial lighting were off.

Table 1 Illuminance on measuring points (lx)

TIME	09:00	10:00	11:00	13:00	14:00	15:00	16:00
7.5 M HALL							
1	1244	3200	5590	4196	3731	2006	208
2	2109	5648	9460	5602	5141	3075	212
3	2200	6400	10212	5367	4998	3837	167
4	1898	4738	7640	5305	5906	3867	206
5	1695	4421	8070	5832	4943	3647	252
6	1091	3189	5282	3556	3148	2503	164
7	4107	5211	5995	4602	5797	3381	102
8	6304	8683	10143	8500	9547	5688	219
9	6566	8051	10282	7609	5016	5939	353
10	6096	9556	12596	7614	7274	5669	595
11	4609	8240	12097	7002	7507	5506	694
12	3370	5920	6508	3719	4096	3289	447
13	1005	4024	5133	3740	3174	2210	170
14	1624	6042	7922	6386	5596	4036	204
15	1654	6212	8440	8372	6314	4371	216
16	1861	4793	7422	7191	6925	4057	202
17	1829	4748	7666	6032	5723	3751	196
18	997	2915	4884	3308	3444	3176	235
9.9M HALL							
19	1722	2553	3049	2527	2179	800	18
20	1867	2682	3360	2586	2299	293	19
21	2149	2882	3568	2534	2136	282	16
22	1965	2888	3519	2525	2088	263	24
23	2107	3003	3849	2818	2116	255	21
24	1128	2811	3574	2954	2227	250	23
25	1029	2400	3422	2804	2343	229	18
26	1041	2319	3490	2882	2809	386	18
27	1395	2431	2747	3030	2718	448	25

Temperature stratification

Figure 5 displays measured air tempeature values on two horizontal measuring points – one is tagged No.1 in the inernal hall, the other tagged as No.13 in the perimeter hall. Indoor air termperature and temperature gradients increase with outdoor air temperature. The indoor air temperature at 1.5m height of No.1 measuring points is higher than 30°C around 2:00pm. That may cause thermal discomfort for occupants.

Relative humidity

Figures 6 and 7 display measured relative humidity values on measuring points in internal and perimeter hall. The peak value is lower than 60% and occurs in the afternoon.

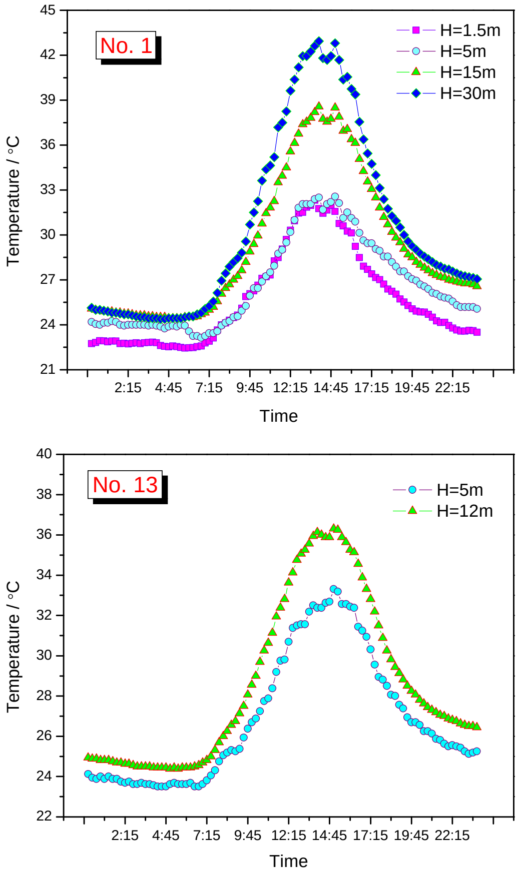


Figure 5 Temperature stratification on measuring points tagged No.11 and 13

Supply air temperature and velocity

Measured values of supply air temperature in the internal hall vary within a range from 13.8°C to 18.5°C; those in the perimeter hall vary from 15.0°C to 18.6°C. Measured values of supply air velocity in the internal hall vary from 1.1 m/s to 5.4 m/s; those in the perimeter hall vary from 1.0 m/s to 5.5m/s. Supply air temperatures are lower in the internal hall than those in the perimeter hall, but values of supply air velocity are greater in the internal hall than those in the perimeter hall.

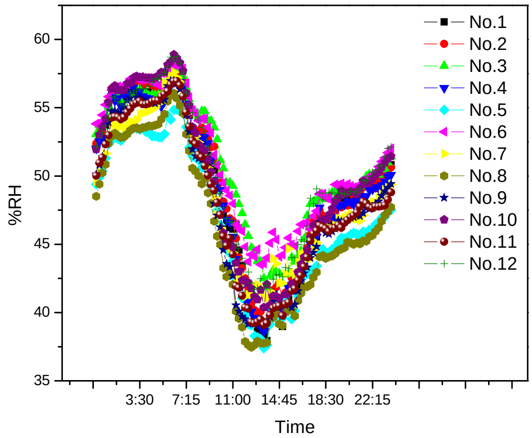


Figure 6 Relative humidity values on 12 measuring points in the internal hall

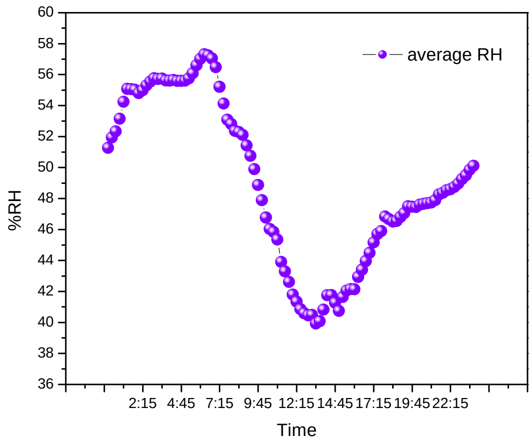


Figure 7 Average relative humidity of 9 measuring points in the perimeter hall

COMPUTER SIMULATION

CFD simulation

The CFD simulation was carried out using STAR-CD 3.26.

Model and boundary condition

In the CFD model, the roof of the waiting hall is simplified into three parts: the small blue area is axial flow exhaust fan area; the pink is the glass roof without shading; the light blue is the glass roof with shading blinds (See Figure 8). The air is supplied through diffusers at 4 m height from the floor on the side walls and pillars in the space and returned through openings under the seats in the 7.5m internal hall and openings in the ceiling in the 9.9m perimeter hall. Figure 9 gives the geometry of inside space, openings, and air diffusers. Boundry conditions were initially extracted from as-built design drawings and specifications but have been calibrated with measured data such as solar radiation and ambient temperature.

Figure 8 CFD geometry model

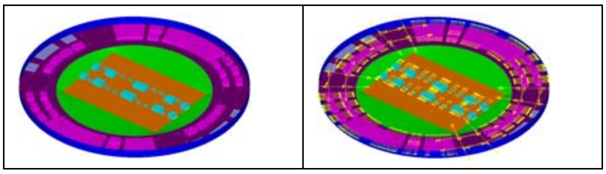


Figure 9 Geometry and air supply openings

Measured data including outdoor air temperature, solar radiation, supply air temperature and velocities are input as boundary conditions of the model. κ-ε turbulence model is used in the simulation. Table 2 lists the input values of turbulent kinetic energy κ in different positions.

Table 2 Boundary condition (input values of turbulent kinetic energy)

	FAÇADE	**ROOF WITH SHADING**	**ROOF NO SHADING**
κ (m^2/s^2)	2.71	0.53	1.9

Simulation results analysis

Figures 10 and 11 indicate CFD simulation results of air velocity and temperature distribution at 1.5m height from the floor at 2:00pm when outdoor air temperature reach its peak. Air velocity near air diffuser is higher than other areas in the internal hall. Compared to the internal hall, the air flow distribution is more uniform with lower air velocity. Simulation results of air temperature distribution show similar effect - lower air temperature corresponding to higher air velocity.

Comparison with site measurement

In consideration of symmetry of the model, half of the measuring points are selected to compare with the simultion results. The comparison shows that the simulation results closely match the measured data (See Table 3). Figure 12 gives the comparative results of two measuring points. Air temperature gradient is small near the floor and ceiling but great in the mid of the height in the spaces. Temperature stratification effect is significant according to the results of simulation and site measurement.

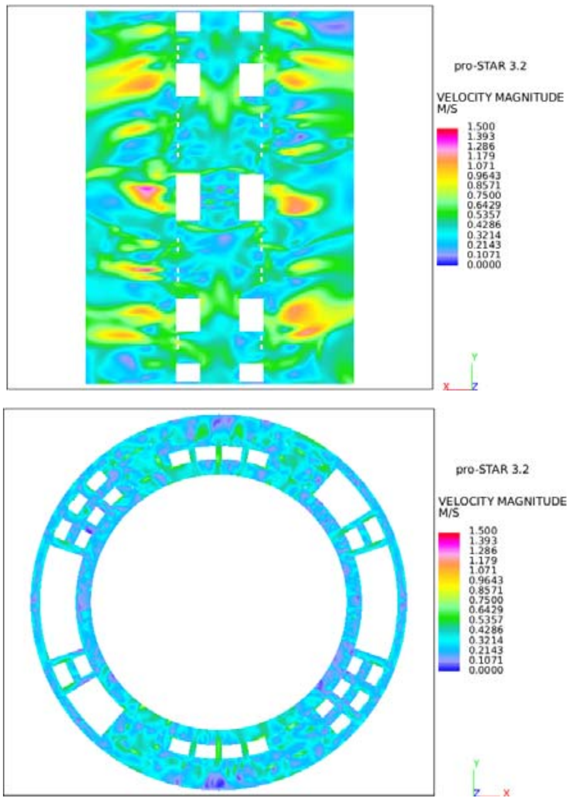
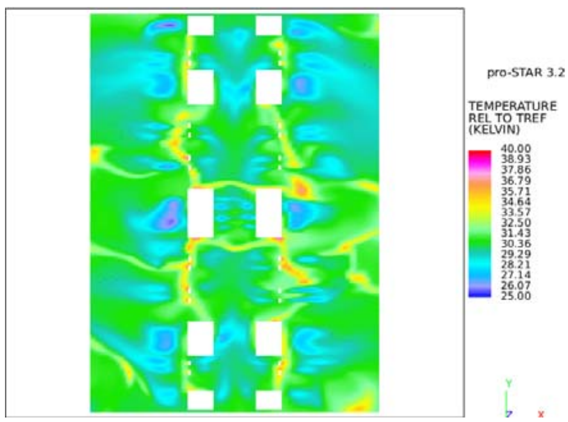


Figure 10 Air velocity distributions at 1.5 m height from the floor



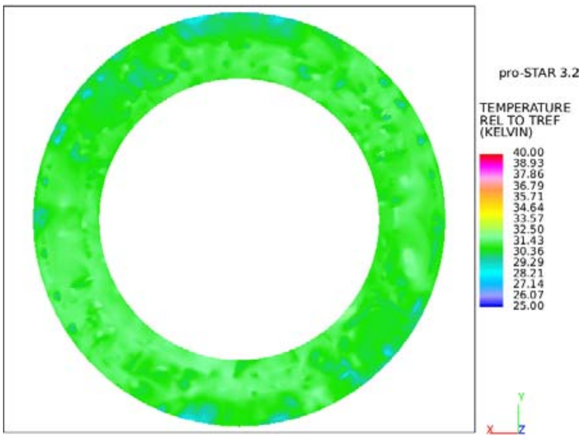


Figure 11 Air temperature distributions on the plan of 1.5 m height from the floor

Table 3 Differences of simulated temperatures compared with measured values at 2:00 pm

TESTING POINTS	**1**	**2**	**3**	**4**	**5**	**6**
1.5m	1.39%	1.32%	5.17%	1.41%	0.06%	1.17%
5m	2.15%	1.77%	7.65%	1.64%	1.05%	1.42%
15m	1.39%	0.38%	5.77%	5.34%	1.51%	0.03%
30m	0.05%	1.21%	6.70%	1.79%	1.92%	2.04%
TESTING POINTS	**13**	**15**	**17**	**19**		
5m	0.33%	0.98%	0.79%	0.27%		
15m	0.90%	1.64%	2.31%	1.92%		

Daylight simulation

Daylight simulation is implemented using the Radiance simulation engine embedded in IES VE 5.5 (Integrated Environmental Solutions Virtual Environment), a commcial software developed by Integrated Environmental Solutions Ltd. UK..

<u>Model development</u>

Figure 13 shows the IES model and Table 4 lists performance data of construction materials of roof and façade built in the model. Data of thermal or optical properties in the model is from as-built design drawings and specifications.

<u>Comparison between simulation and measurment</u>

CIE overcast was used as the sky condition in the simuation due to the unavailability of instrument that physically measures sky conditions. The illumiance distribution on 1.5m high working surface at 9:00am, 11:00am and 1:00pm is simulated. Figure 14 and Table 5 show good agreement between measured illuminance and simulation results.

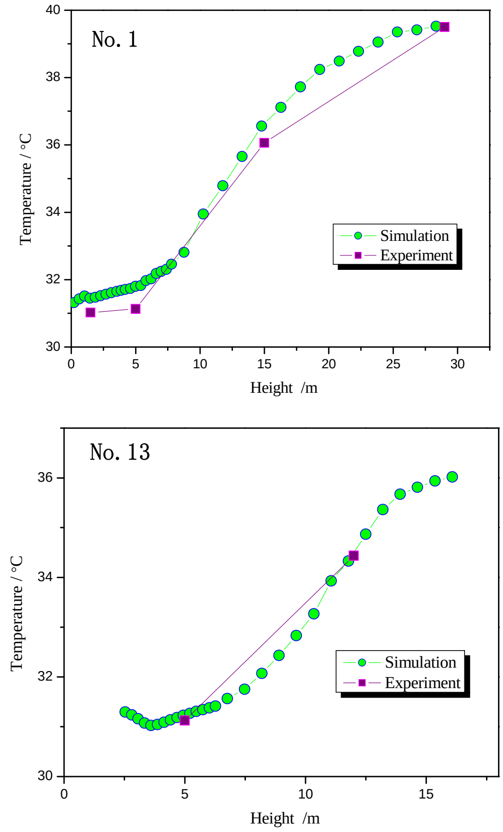


Figure 12 Comparison of air temperature between simulation and site measurement on measuring points 1 and 13 at 2:00 pm

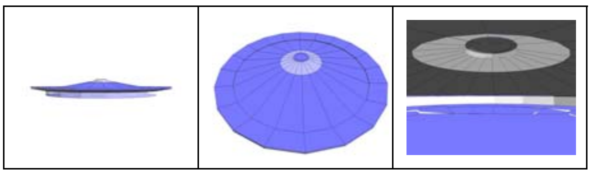
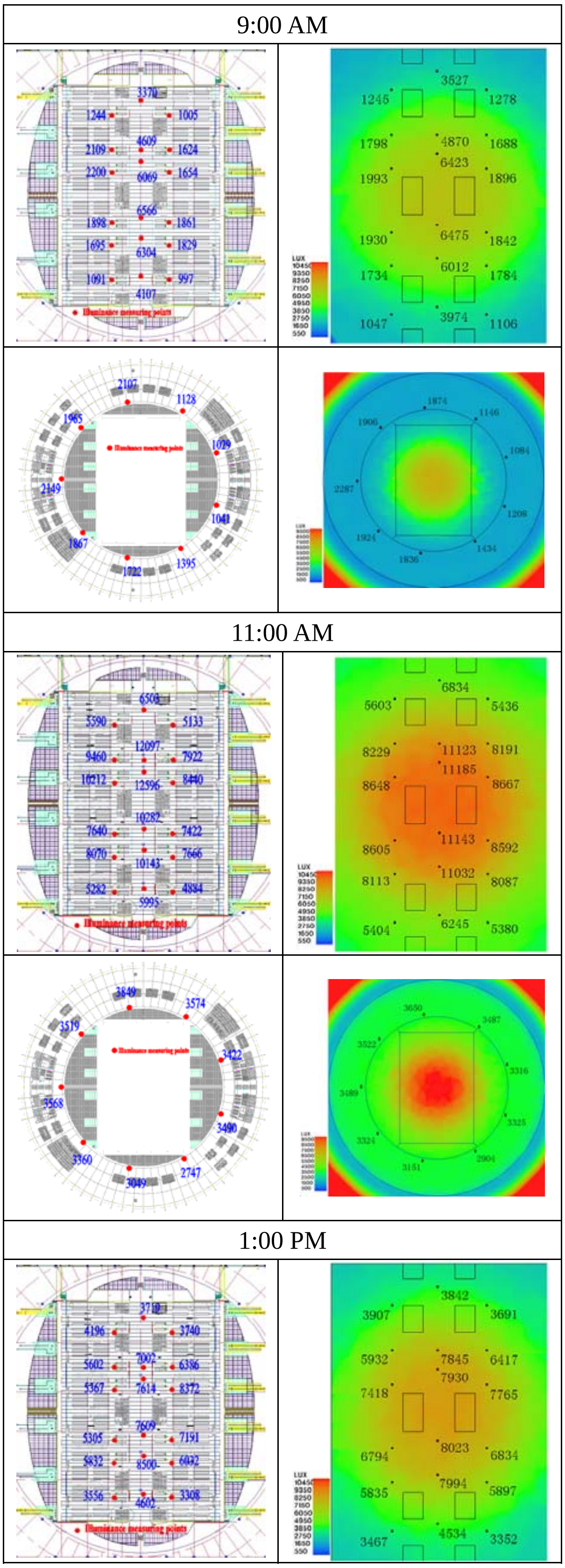


Figure 13 Radiance model

Table 4 Input data of construction for Radiance model

CONSTRUCTION		**VT**	**VR**	**SC**
Roof	Shading blinds		0.9	
	Polycarbonate glass	0.55	0.15	0.47
	Porous sound absorption board		0.7	
Façade	Double-pane clear glass	0.43	0.47	0.37

VT: visible transmittance; VR: visible reflectance; SC: shading coefficient



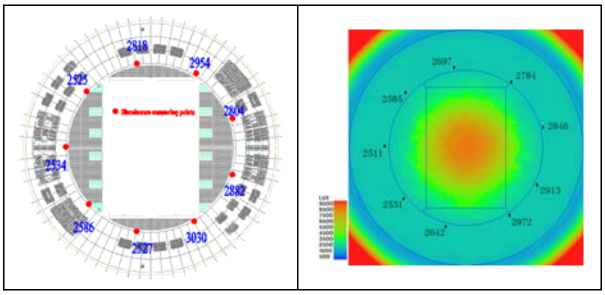


Figure 14 Comparison between measured illuminance and simulated values

Table 5 Differences of simulated illuminance compared with measured values

TESTING	9:00am	11:00am	1:00pm
1	0.08%	0.23%	6.89%
2	14.75%	13.01%	5.89%
3	9.41%	15.32%	38.22%
4	1.69%	12.63%	28.07%
5	2.30%	0.53%	0.05%
6	4.03%	2.31%	2.50%
7	3.24%	4.17%	1.48%
8	4.63%	8.76%	5.95%
9	1.39%	8.37%	5.44%
10	5.36%	11.20%	4.15%
11	5.66%	8.05%	12.04%
12	4.66%	5.01%	3.31%
13	27.16%	5.90%	1.31%
14	3.94%	3.37%	0.49%
15	14.63%	2.69%	7.25%
16	1.02%	15.76%	4.96%
17	2.46%	5.49%	2.24%
18	10.93%	10.16%	1.33%
19	6.62%	3.35%	4.55%
20	3.05%	1.07%	2.13%
21	6.42%	2.21%	0.91%
22	3.00%	0.09%	2.38%
23	11.06%	5.17%	4.29%
24	1.60%	2.43%	5.75%
25	5.34%	3.10%	1.50%
26	16.04%	4.73%	1.08%
27	2.80%	5.72%	1.91%

The illumiance level near the center of the internal hall is much higher than perimeter area, because no external shadings are provided to the center area of the glass roof and daylight directly enters the space.

CONCLUSION

This paper has described comparative study between simulation and field measurement of thermal and daylight performance of a highly glazed atrium-type space – the waiting hall of Shanghai South Railway Station. Weather data, indoor vertical temperature stratification, daylight illuminance distribution, supply air temperature and velocity were measured and recorded from July 27th to 28th, 2007 – a typical summer period in Shanghai. Some of the measured data are used as boundary conditions of the CFD simulation model, some are compared with simulation results for calibration. Two types of software – STAR-CD and IES VE – are used to build the CFD and the daylight model respectively.

(1) Simulation results from CFD model agree with the measured values well. It is reliable to use simulation tools, with proper boundary conditions, to predict complex thermal-air-coupled phenomena such as vertical temperature gradient of large highly-glazed spaces, where site measurements are normally difficult to be carried out. Accurate prediction of building performance may lead to generic improvement of designing such atrium-type spaces, for instance, amended design of external shading, better selection of glass performance, etc..

(2) Simulation results from daylight modeling also generally agree well with physical measurement but significant discrepency exists on some measuring point (2, 3, 4, 13, 15, 18, 26) at some specific hours.To authors' speculation two reason may account for the discrepency: (a) the discrepancy between CIE Overcast sky condition and actual sky condition during the measurement, (b) the accuracy of modeling specific external shading materials on the roof that is, though, extracted from as-built design specification.

(3) The site measurement and CFD simulation of the indoor air temperature distribution show significant vertical temperature stratification in the waiting hall. This result validates the design performance and energy efficiency of supplying conditioned air at 4m height of the hall to provide thermal comfort to 2.5m-below occupant zones only.

(4) Both site measurement and Radiance simulation of daylight distribution in the waiting hall show much higher illuminance level than what design standard requires without artificial lighting during daytime. This means that suficient amount of daylight the highly-glazing roof introduced into the space can save a significant amount of energy artificial lighting consumes. However, the measured illuminance values as high as 10,000 lux causes glare and visual discomfort within the space. This is the adverse effect designers and building owners don't expect to have in the purpose of fully using daylight.

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