

Influence of Lawns on the Summer Thermal Environment and Microclimate of Heritage Sites: A Case Study of Fuling Mausoleum, China

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Influence of lawns on the summer thermal environment and microclimate of heritage sites: A case study of Fuling mausoleum, China

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Equal Contribution

Abstract: The thermal environment and microclimate of heritage sites has been severely impacted by rapid urbanization. This study collected various meteorological measurement data as a reference for computational fluid dynamics (CFD) simulation settings. Then CFD was applied to simulate the impact of lawns on the thermal environment and microclimate of Fuling Mausoleum. We found that lawns and soil can cool the air through evaporation, and thus have a specific cooling effect on the bricked ground. After lawns were planted, the bricked ground temperature decreased by 1.56–17.54°C than that before lawns were planted at 14:00, a decrease of 2.68%–24.20%. Under normal circumstances, when the wind speed or relative humidity increased, the ground temperature dropped. Greenbelt vegetation can adjust the microclimate and human thermal comfort indicators. The consistency of the difference between the actual measurement and the CFD simulation results shows that CFD simulation can thus accurately reflect the internal temperature field distribution if the selection of simulation parameters is reasonable. Theoretical calculation and analysis, experimental measurement research, and modern computer simulation analysis methods applied together constitute a complete system for studying modern physical environmental problems and can provide reliable and economic results.

Keywords: Thermal environment; Microclimate; Fuling mausoleum; Heritage site; CFD simulation

1. Introduction

As a result of the rapid expansion of urban areas, heritage sites that were initially located in the suburbs or rural areas of many cities have gradually become important inner city areas. The phenomenon of urbanization has caused severe impacts and changes to the natural environment, and the environmental landscape is also deteriorating. The natural vegetation cover has been replaced by buildings and urban infrastructure, which results in the well-known urban heat island effect [1].

Several adaptation measures have been put into practice for their potential to affect the urban microclimate, mainly to reduce high temperatures [2,3,4,5,6]. The greening and vegetation of urban areas are the most investigated adaptation approaches as they can reduce the surface temperature of the surrounding environment [3,7,8]. The ambient temperature can also be decreased by evaporation and transpiration of plants. The main methods to study the effectiveness of vegetation in mitigating the heat island effect are field measurements [7,9,10], ground control experiments [11], and computational fluid dynamics (CFD) simulation [12,13,14,15,16,17,18]. Of these, CFD evaluates the effectiveness of vegetation coverage in detail on the outdoor urban microclimate, which is an economical and practical method of achieving accurate predictions. Hong and Lin [19] used the outdoor thermal simulation platform to discover the influence of the green layout on the outdoor environment and pedestrian thermal comfort. Bruce and Fleer [12] used CFD and ENVI-met models to simulate the microclimate and studied the impact of ground greening on the thermal stress coverage of small parks. Dimoudi and Nikolopoulou [13] used CFD model to compare the cooling effect of different methods and the vegetation arrangement in general building facilities. Li and Yu [20] used CFD to simulate the thermal environment and residential microclimate around a single building. They verified their simulation by comparing between the measured data with simulated temperature of the outdoor thermal environment around buildings. Bowler et al. [7] conducted an empirical study on the effect of urban greening for cooling effect. The main emphasis of previous research is on the evaluation of the indoor microclimate of heritage buildings and how to improve the comfort of users. Corgnati et al. [21] also described a methodology for evaluating the microclimate in museums between traditional convenience and thermal comfort. According to European standards such as EN 15251 [22], La Gennusa et al. [23] analyzed the indoor climate and indoor environment in historical Italian buildings, including temperature and humidity.

CFD technology involves the solving of various conservation control partial differential equations describing fluid flow, heat transfer, and mass transfer and the visualization of the different solved flow or heat transfer phenomena. CFD technology, theoretical analysis and experimental research have become three essential fluid mechanics research methods. These three methods complement each other [24,25]. To our knowledge, few studies focus on the outdoor thermal environment and microclimate for heritage sites. Because of urbanization around heritage sites, the summer temperatures are increasing. This study focused on the cooling effect of grassland and vegetation on the environment in summer. On the basis of actual measurement, the CFD simulation experiment was applied to analyze the cooling effect of the vegetation.

First, infrared images and precise measurements are taken with an infrared thermal imaging camera to collect various physical data in meteorology as a reference for CFD simulation settings. Then, CFD was used to simulate the impact of lawns on the thermal environment and microclimate of the heritage site. The research includes: 1) Analysis and comparison of the actual measurement with simulation results; 2) Analysis of the simulation results before and after lawns were planted; 3) Analysis of the simulation

results at different wind speeds and relative humidity; and 4) Analysis and comparison of the actual measurement of microclimate with the human thermal comfort index value.

2. Methodology

2.1 Study site

Shenyang is located in central Liaoning Province, southern northeast China (41°12'N–43°02'N, 122°25'E–123°48'E). Fuling Mausoleum is located in the eastern suburbs of Shenyang. It is the tomb of the Qing patriarch Nurhachi and his queen Yehenala and is one of the three mausoleums of Shengjing. Fuling Mausoleum was built in 1629 and was completed in 1651. After a great deal of construction works during the Shunzhi, Kangxi, and Qianlong periods of the Qing Dynasty, a large-scale and well-equipped ancient emperor tomb complex was formed. When it was first built, it was called “Xianhan Mausoleum” or “Taizu Mausoleum”. In the first year of Chongde (1636), it was named “Fuling Mausoleum”, which implies the long-lasting fortune of the Qing Dynasty [26]. In 2004, The Three Mausoleums of Shengjing (referring to Fuling, Zhaoling, and Yongling Mausoleums), were included on the UNESCO World Heritage Site List [27].

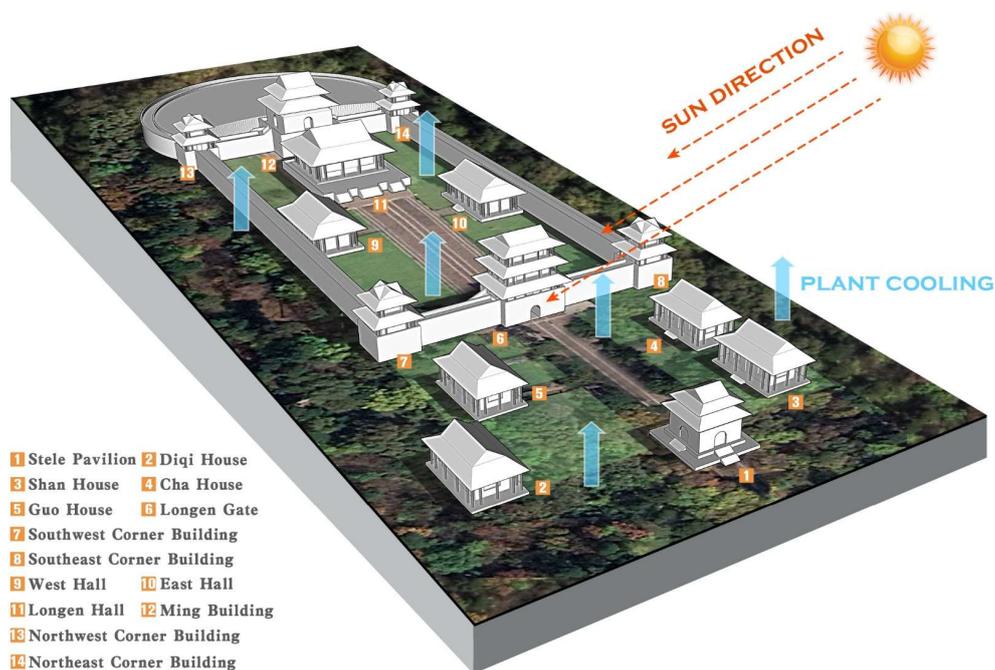


Fig.1 The environment surrounding Fuling Mausoleum (white is the CFD simulation model).

Fuling Mausoleum has a detailed layout and distinct levels and has a total area of approximately 194,800m². It is shaped like an inner city with an outer wall. It comprises three parts—the front yard, the square city and the treasure city—and it gradually increases in elevation from south to north. The mausoleum building complex remains relatively intact [28]. There are 32 existing ancient buildings, which are symmetrically distributed with the Shinto as the central axis. It is a complex of imperial tombs that integrates the characteristics of the Manchu and Han ethnicities, which differs from the tombs of the Ming Dynasty and those built after the Qing Dynasty [26]. This article focuses on the three main buildings of Fuling Mausoleum: Stele Pavilion, Long'en Gate and Long'en Hall (Fig. 1).

2.2 On-site measurements

July is the hottest month of the year in Shenyang. The daily average temperature is between 28 and 29°C, and the weather is usually in the range 24–32°C. The maximum ground temperature can reach 63°C. In July, the average wind speed is 3.64–3.86 m/s and the wind direction is mainly southerly [29]. On July 12, 2020, when field measurements were taken at Fuling Mausoleum, the weather was clear and the wind speed was relatively low. To study the impact of lawns on the summer thermal environment and microclimate of Fuling Mausoleum, the project team members selected five-time points—10:00, 11:00, 12:00, 13:00, and 14:00—and conducted the field measurements at these times. The measuring instruments (Table 1, Fig.2) and measurement groups taken were as follows:

Table 1 Measuring instruments and measuring parameters

Measuring instruments	Measuring parameters	Instrument accuracy
Black bulb thermometer Temperature and humidity tester WBGT Tester	Air temperature	±0.1°C
	Black bulb temperature	±0.1°C
	WBGT Heat index	±0.1°C
	Relative humidity	±5% RH
Anemometer	Wind speed	±3% 或 ±0.1dgt
Infrared thermal imaging thermometer	Object temperature imaging	±2% 或 ±2°C
Heat flux sensor	Soil heat flux density、 Heat flux density of bricked ground	20-100 μW·w ⁻¹ ·m ²



Fig. 2 Measuring instruments: (a) black bulb thermometer, (b) anemometer, (c) heat flux sensor (photos by Xiaoyu Wang).

(1) Outdoor thermal environment. The primary measurement data were air temperature, black bulb temperature, relative humidity, wind speed, and the wet bulb globe temperature (WBGT) value. Measurement were taken 1.6 m from the ground in the open area in front of Long'en Gate to obtain biological data to describe the environment, and to measure the thermal environment and microclimate physical data of the surrounding lawns and the bricked ground.

(2) Infrared thermal imaging. The primary measurement contents were the real-time temperature of the lawns and the bricked ground. The measurement locations were selected in front of the Stele Pavilion, Long'en Gate, and Long'en Hall and included the bricked ground and lawns to the left and right of these structures. Infrared thermal imaging photos were taken to determine the real-time temperature at each measurement point.

(3) Surface heat flux measurement. The primary measurement contents were the heat flux data for the bricked ground and the green soil. The heat flow measurement points were placed on the floor of the bricked ground and at 10 cm soil depth in the lawns to measure the heat flux data of the different ground surfaces. The surface of the lawns was in an endothermic state and the measured heat flux was between -16.9 and -16.8 W/m^2 , whereas the bricked ground was in an exothermic state, and its heat flux was between 90.7 and 137.9 W/m^2 (Table 2).

Table 2 Actual measurement data

Time (Hour)	Air temperature (°C)	Wind speed (m/s)	Relative humidity(%)	Heat flux of lawns (W/m^2)	Heat flux of bricked ground (W/m^2)
10	26.1	3.6	68	-16	90.7
12	31.4	4	46.9	-16.8	108.9
14	33.7	5	40.1	-16.8	137.9

2.3 CFD approach

Based on the actual measurement and theoretical research, the heat flux determined using ANSYS/Fluent was used to set two types of lawns and bricked ground to simulate the thermal environment and microclimate [30]. The heat flux of lawns and the bricked ground was measured as a reference. The grass material was found to absorb heat, thus the heat flux was set to a negative value for these areas. Conversely, the brick material emit heat, thus the heat flux was set to a positive value for these areas.

(1) Calculation area and boundary condition settings

The calculation area was set to a rectangular parallelepiped area (1200 m long, 400 m wide, and 70 m high). The calculation area was mainly based on the ancient buildings from Stele Pavilion to Ming building and the surrounding environment. The inlet of the simulation calculation range was set to the velocity inlet, the outlet was set to the pressure outlet, the boundary condition of the ground was set to the wall, and the external calculation domain was set to the symmetry to assume actual atmospheric environmental conditions.

(2) Mesh settings

The mesh system setting was a numerical calculation method based on the finite volume method. The calculation area was divided into the appropriate mesh, and calculations were performed to determine the mass, momentum, and energy conditions in each mesh. In this study, the mesh was generated using ANSYS-ICEM CFD software using tetrahedral elements in the fluid domain. The mesh contains between 2.35 and 2.4 million tetrahedral elements (Fig. 3).

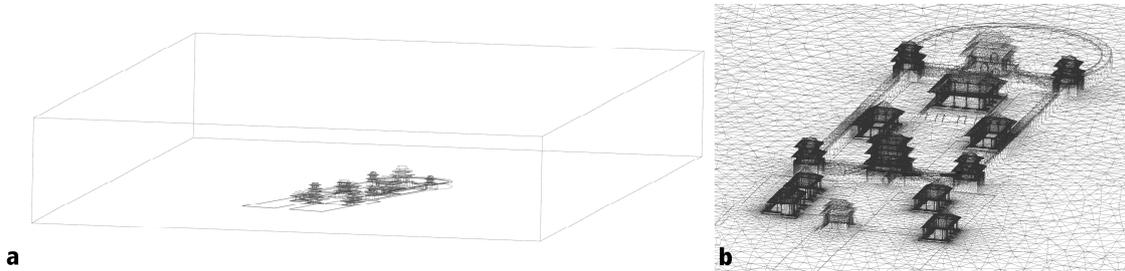


Fig.3 (a) General views of the computational domain (geometry and mesh) for Fuling Mausoleum. (b) Detail of the mesh refinement with tetrahedral elements.

(3) RNG $k-\varepsilon$ Model

We used the RNG $k-\varepsilon$ model for viscous modeling. The RNG $k-\varepsilon$ model was proposed by Orszag and Yakhot [31]. Although similar in form to the standard $k-\varepsilon$ model, the RNG $k-\varepsilon$ model is more accurate and reliable for a wider class of flows [32]. The turbulence kinetic energy, and its rate of dissipation, ε , are obtained from the following transport equations [30]:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left(\alpha_k \mu_{eff} \frac{\partial k}{\partial x_j} \right) + G_k + G_b - \rho \varepsilon - Y_M + S_k \quad (1)$$

and

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_i}(\rho\varepsilon u_i) = \frac{\partial}{\partial x_j} \left(\alpha_\varepsilon \mu_{eff} \frac{\partial \varepsilon}{\partial x_j} \right) + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_{3\varepsilon} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} - R_\varepsilon + S_\varepsilon \quad (2)$$

where G_k and G_b represent the turbulence kinetic energy generated from the mean velocity gradient and buoyancy, respectively; Y_M represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate; α_k and α_ε denote the inverse effective Prandtl numbers for k and ε , respectively; and S_k and S_ε are user-defined source terms.

(4) Wind profile

Regarding the wind boundary layer over the terrain, the velocity profile specifying the inlet boundary condition for each simulation was defined according to this well-established equation [33],

$$U_z = U_{10} \left(\frac{z}{10} \right)^{n_p} \quad (3)$$

Where U_z denotes the air velocity which depends on height z ; U_{10} is the air velocity at the height of 10 m (assumed to be 4 or 10 m/s); and n_p is the Hellman exponent, which depends on the atmospheric stability and the nature of the terrain. n_p near the suburbs of the city is assumed to be 0.22 [34].

(5) Settings of the numerical simulation scheme

The real values collected according to actual measurement served as the basis for the verification of the numerical simulations. The impact of lawns and bricked ground on the thermal environment of ancient buildings was considered through the relative evaluation of the various physical values. The basic parameters of each material are shown in Table 3 [35]. The settings of the specific numerical simulation scheme are shown in Fig. 4.

Table 3 Basic parameters of each material

Material	Density ($\text{kg}\cdot\text{m}^{-3}$)	Specific heat capacity ($\text{J}\cdot\text{kg}^{-1}\cdot\text{k}^{-1}$)	Thermal Conductivity ($\text{W}\cdot\text{m}^{-1}\cdot\text{k}^{-1}$)	Absorption coefficient	Refractive coefficient
Bricked ground	2344	750	1.00	0.87	0.90
Wall	1800	840	1.00	0.73	0.92
Lawns	700	2310	1.20	0.00	0.20

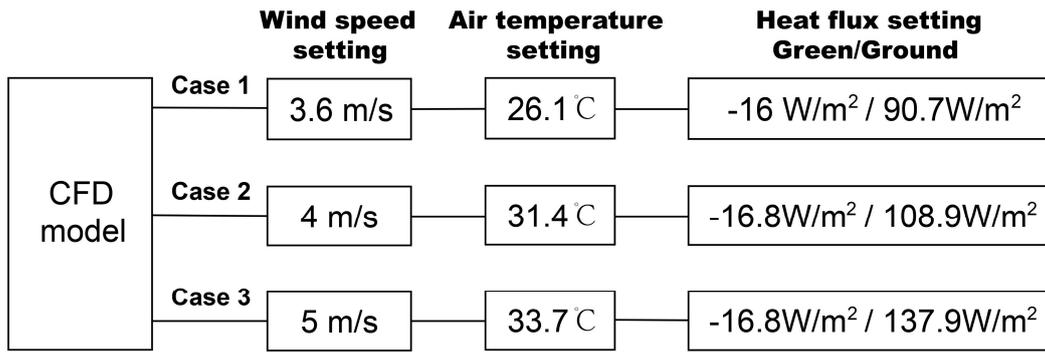


Figure 4. Settings of the specific numerical simulation scheme.

3. Results and discussion

The heat exchange and distribution in the thermal environment of this site constitute a complex system, including various heat transfer processes such as convection, radiation, and heat conduction among mountains, rivers, air, and the earth. We focus on the influence of lawns on the summer thermal environment and microclimate of the architectural heritage site, which is mainly reflected in how wind

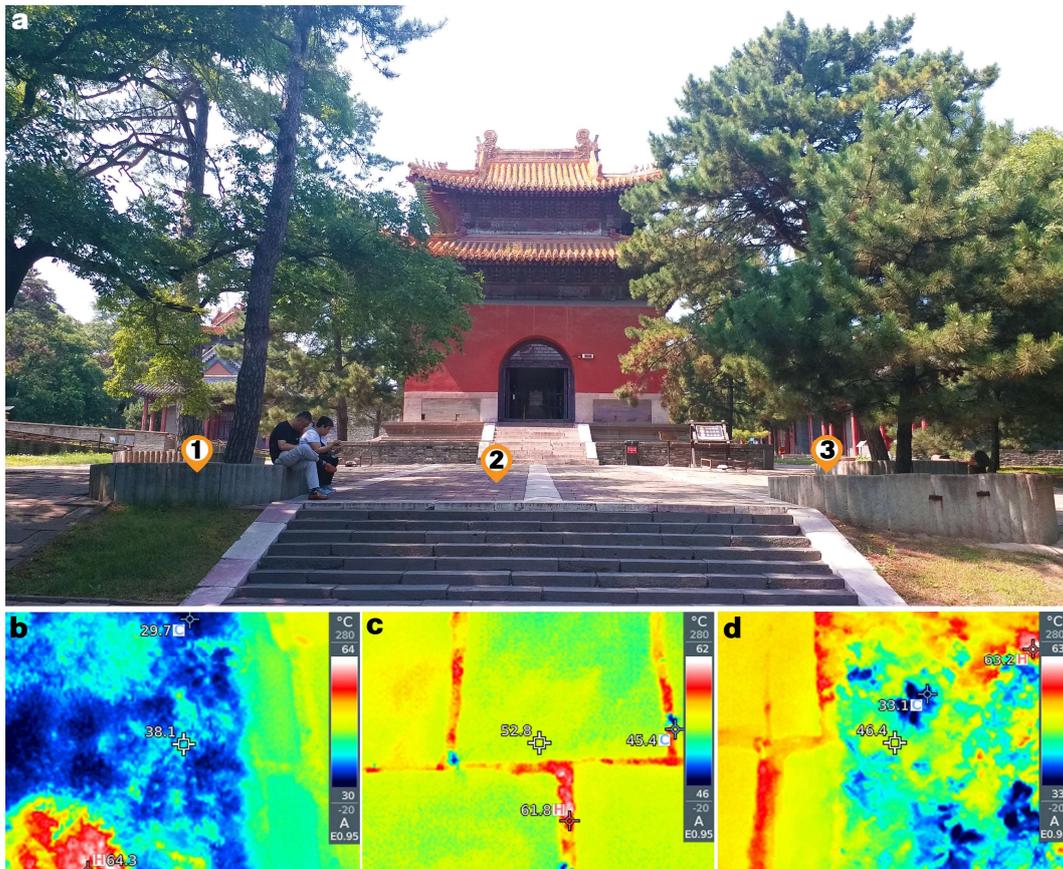


Fig.5 Photo and infrared images of the site in front of Stele Pavilion: (a) photo of the site and overhead of (b) lawns to the left, (c) bricked ground, (d) lawns to the right (photo by Xiaoyu Wang).

speed, temperature, and humidity affect the cooling effect of vegetation.

3.1 Analysis of the actual measurement

The project team took photos and infrared images of the bricked ground and lawns to the left and right in front of Stele Pavilion, Long'en Gate, and Long'en Hall at the five-time points and obtained the data for each measuring point. To accommodate space limitations, we focused on the most explicit infrared image at 14:00 to study the role of local lawns on the thermal environment and microclimate regulation.

Figs. 5–7 present photos and infrared images of the bricked ground in front of Stele Pavilion, Long'en Gate, and Long'en Hall and lawns to the left and right of these sites taken at 14:00 using TESTO thermal imaging camera. The air temperature is affected by solar radiation and ground radiation. The air temperature peaked at around 14:00. After the ground absorbed solar radiation, the temperature also increased. The minimum temperature of green soil was still low, which indicates that the green soil could cool air through evaporation and cause a relatively low surface temperature. However, at the same time, the massive radiation absorption coefficient of the soil allowed it to absorb more heat radiation, which resulted in higher local heat production.

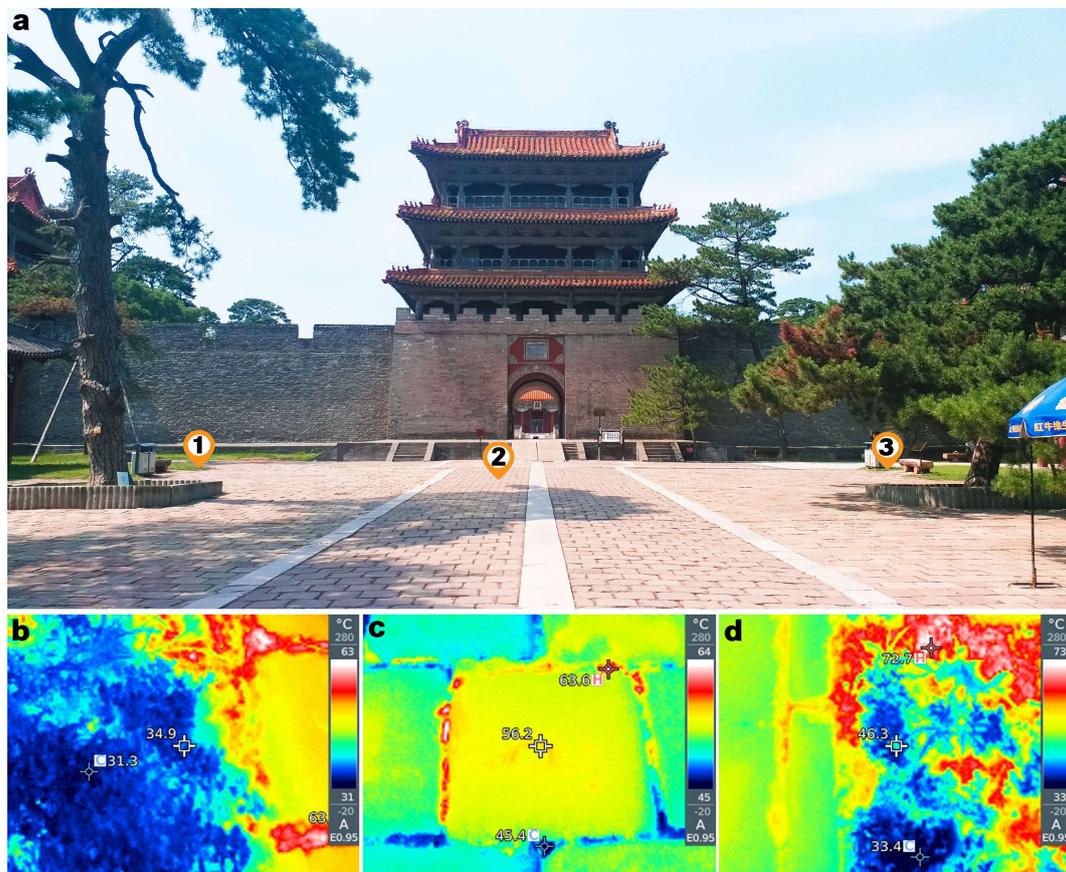


Fig.6 Photo and infrared images of the site in front of Long'en Gate: (a) photo of the site and overhead of (b) lawns to the left, (c) bricked ground, (d) lawns to the right (photo by Xiaoyu Wang).

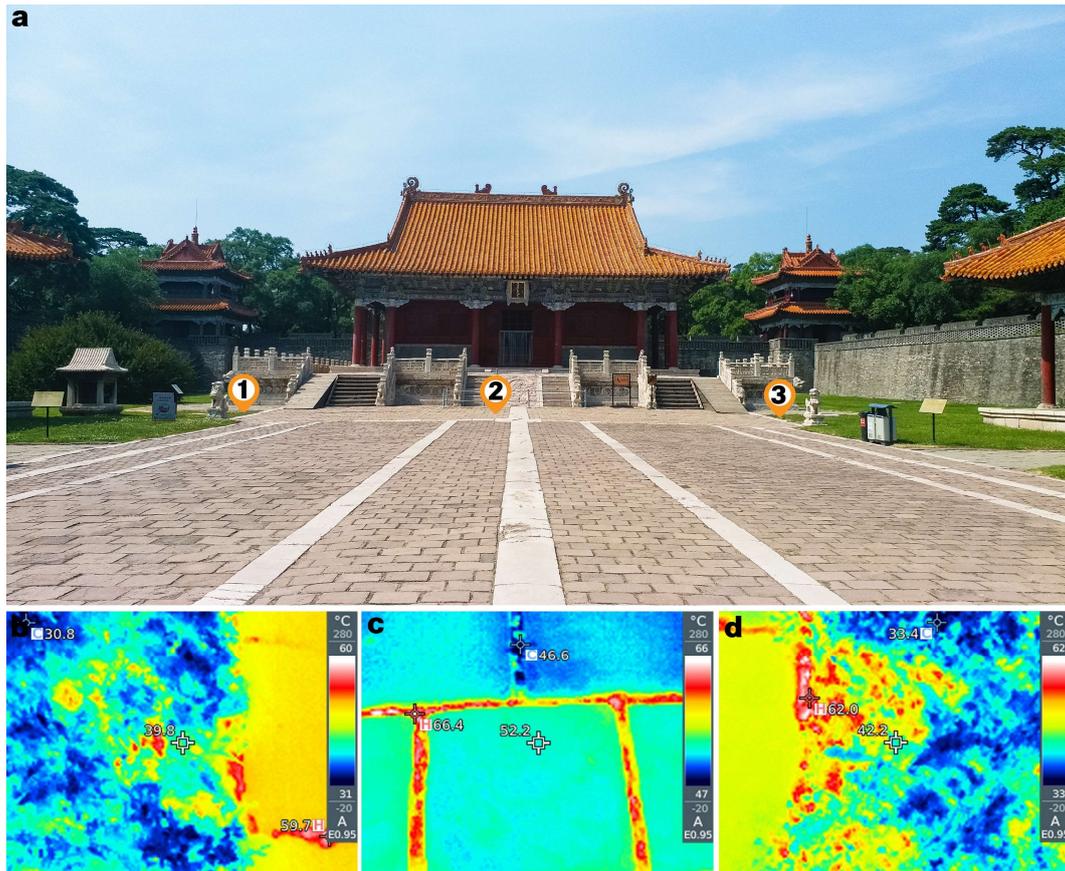


Fig.7 Photo and infrared images of the site in front of Long'en Hall: (a) photo of the site and overhead of (b) lawns to the left, (c) bricked ground, (d) lawns to the right (photo by Xiaoyu Wang).

As the temperature increased, the temperature change increased. The bricked ground did not have the evapotranspiration effect of green soil. The coefficient of absorbing radiation was small; therefore, the minimum and maximum temperature did not change as much as the soil of lawns. However, the greening of the surrounding environment affected on the bricked ground and had a specific cooling effect.

As shown in Figs.5–7, the lowest and highest temperatures of lawns to the left in front of Stele Pavilion were 29.7 and 64.3°C, respectively, those of lawns to the right were 33.1 and 63.2°C; and of the bricked ground were 45.4 and 61.8°C. The lowest and highest temperatures of lawns to the left in front of Long'en Gate were 31.3 and 63.0°C, respectively, those of lawns to the right were 33.4 and 72.7°C; and of the bricked ground were 45.4 and 63.6°C. The lowest and highest temperatures of lawns to the left in front of Long'en Hall were 39.8 and 59.7°C, respectively, those of lawns to the right were 33.4 and 62.0°C; and of the bricked ground were 46.6 and 66.4°C.

3.2 Analysis and comparison of the actual measurement with simulation results

The following relative error formula was used to assess the validity of the calculation results [36]:

$$\delta = \frac{\Delta}{L} \times 100\% \quad (4)$$

where δ is the relative error between the measured value and the simulated value at a given time, Δ is the absolute error at that time (the absolute value of the difference between the measured value and the simulated value), and L is the measured value at the time ($^{\circ}\text{C}$).

The error results of the measured and simulated temperature values of each measuring point on a typical day in each season are given in Table 4.

Table 4 Relative error of the measured and simulated temperature values [31]

Time (Hour)	Relative error δ ratio in each interval (%)			
	$0\% \leq \delta \leq 5\%$	$5\% < \delta \leq 10\%$	$10\% < \delta \leq 15\%$	$\delta > 15\%$
10	26.7%	33.3%	33.3%	6.7%
12	40%	30%	26.7%	3.3%
14	53.3%	36.7%	6.7%	3.3%

The consistency of the difference between the actual measurement and the CFD simulation results indicates that CFD could accurately reflect the internal temperature field distribution if the selection of simulation parameters was reasonable (Figs.8-10). In particular, the difference between the actual measurement and the simulation was smallest at 14:00 and the simulated data were the closest to the actual measured data (see Table 4 and Fig. 10).

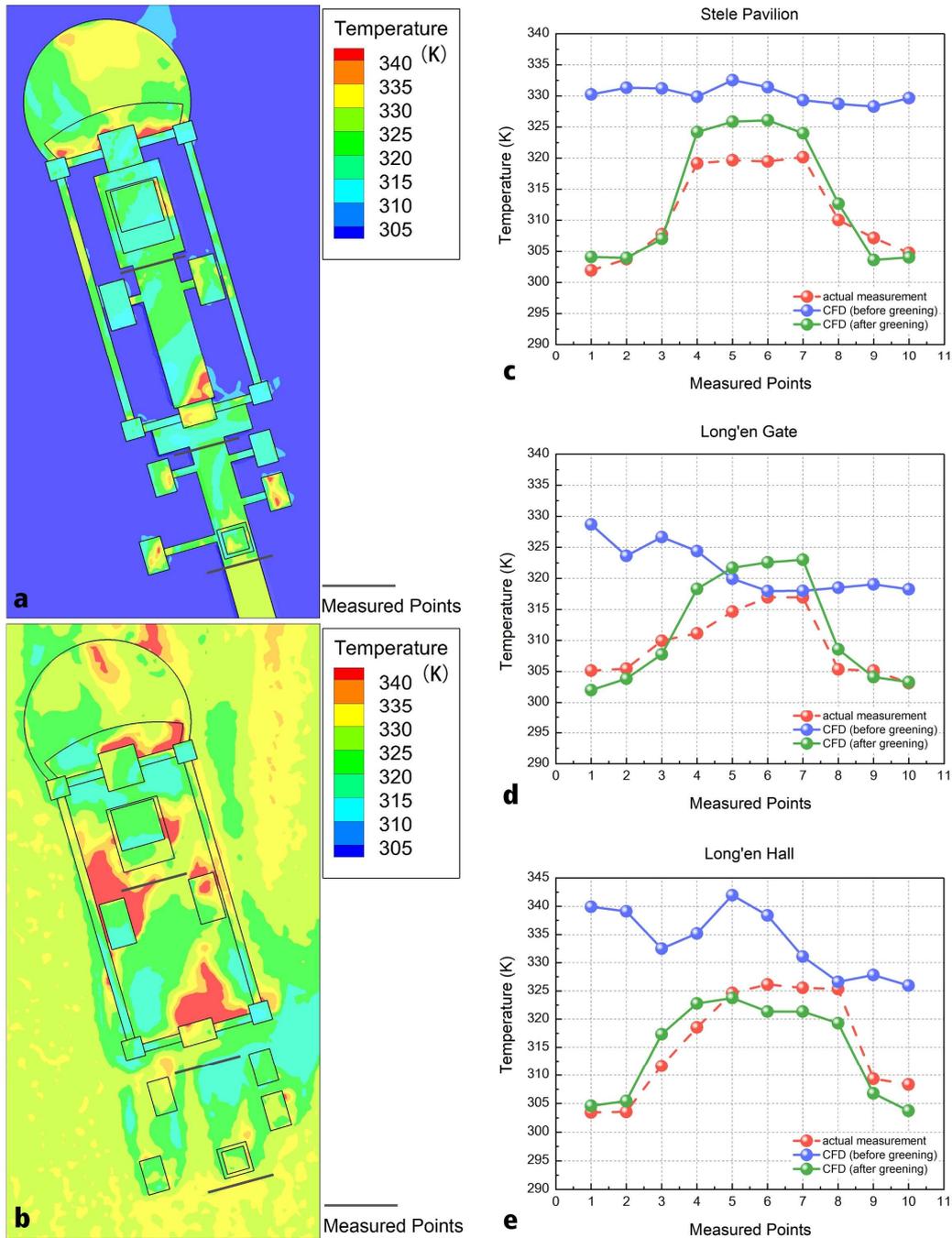


Fig.8 Temperature cloud diagrams and measurement point locations of the numerical simulation at 10:00 (a) after lawns were planted and (b) before lawns were planted. (c-e) Comparison of actual measurement with simulation results in front of Stele Pavilion at 10:00 (c) in front of Stele Pavilion, (d) in front of Long'en Gate, and (e) in front of Long'en Hall.

Fig. 8(a) and (b) show the temperature cloud diagrams and the measurement point locations of the numerical simulation in front of Stele Pavilion, Long'en Gate, and Long'en Hall at 10:00. Fig. 8(c)-(e) show the temperature comparison between the measured and simulated thermal environments in front of Stele Pavilion, Long'en Gate, and Long'en Hall at 10:00. Comparing the measured and simulated temperature curves,

the difference between the measured and simulated values at 10 points was 0.15–7.16°C and the proportion was 0.51%–18.8%. Fig. 9(a)-(b) show the temperature cloud diagrams and the measurement point locations of the numerical simulation in front of Stele Pavilion, Long'en Gate, and Long'en Hall at 12:00. Fig. 9(c)-(e) show the temperature comparison between the measured and simulated thermal environments in front of Stele Pavilion, Long'en Gate, and Long'en Hall at 12:00. Comparing the

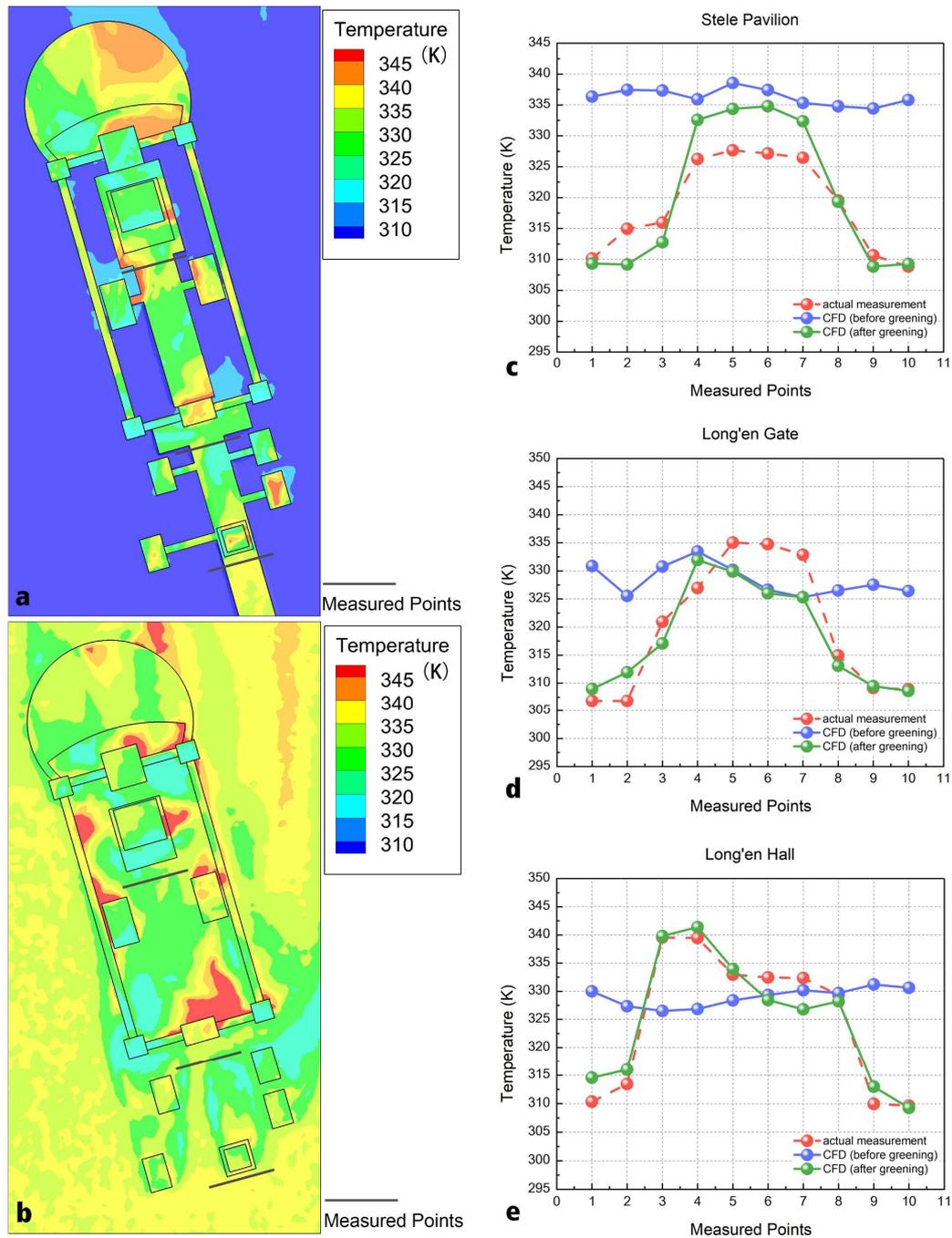


Fig.9 Temperature cloud diagrams and measurement point locations of the numerical simulation at 12:00 (a) after lawns were planted and (b) before lawns were planted. (c-e) Comparison of actual measurement with simulation results in front of Stele Pavilion at 12:00 (c) in front of Stele Pavilion, (d) in front of Long'en Gate, and (e) in front of Long'en Hall.

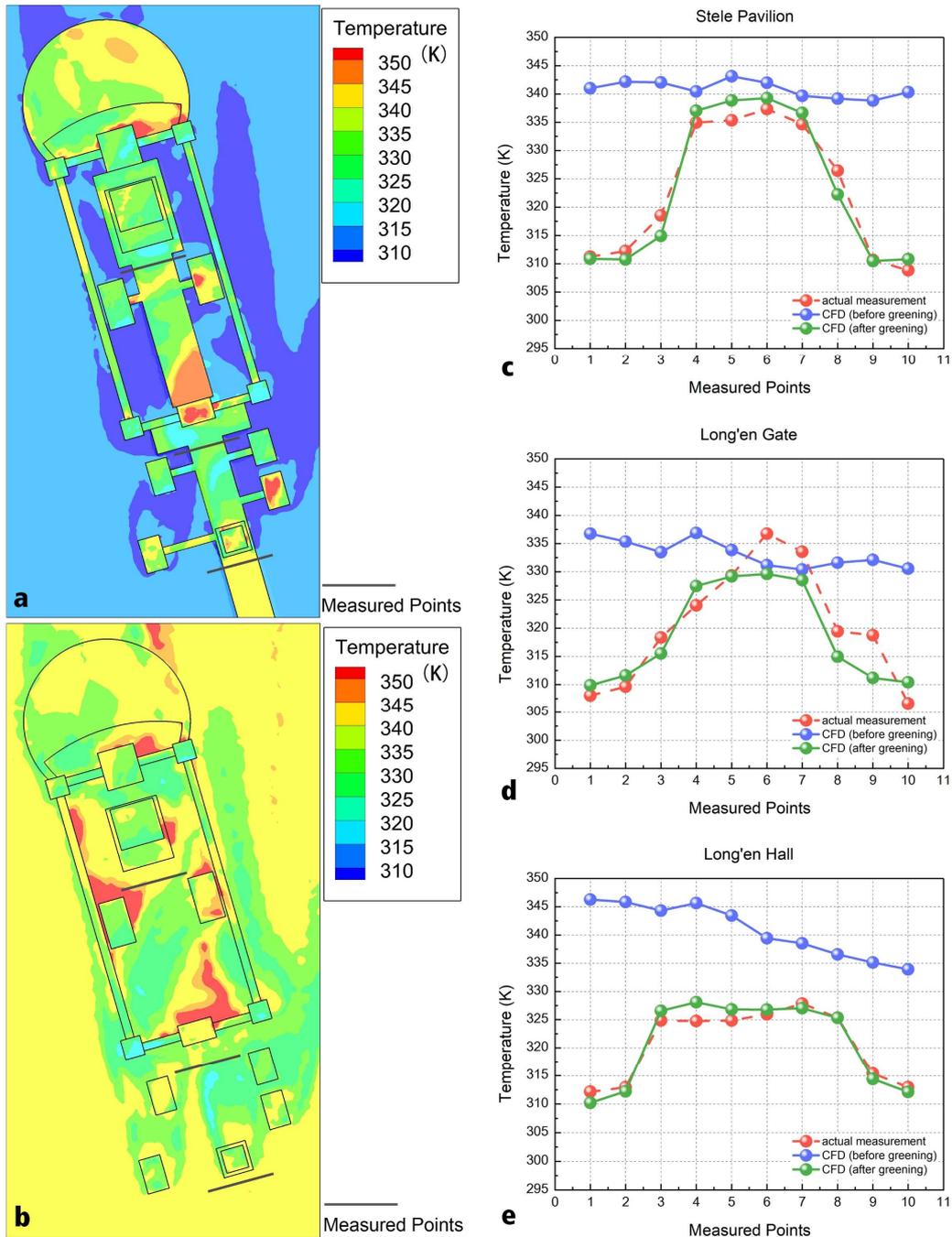


Fig.10 Temperature cloud diagrams and measurement point locations of the numerical simulation at 14:00 (a) after lawns were planted and (b) before lawns were planted. (c-e) Comparison of actual measurement with simulation results in front of Stele Pavilion at 14:00 (c) in front of Stele Pavilion, (d) in front of Long'en Gate, and (e) in front of Long'en Hall.

measured and simulated temperature curves, the difference between the measured and simulated values at 10 points was 0.22-8.74°C and the proportion was 0.48-14.2%. Fig. 10(a)-(b) show the temperature cloud diagrams and the measurement point locations of the numerical simulation in front of Stele Pavilion, Long'en Gate, and Long'en Hall at 14:00. Fig. 10(c)-(e) show the temperature comparison between the measured and simulated thermal environments in front of Stele Pavilion, Long'en Gate, and Long'en

Hall at 14:00. Comparing the measured and simulated temperature curves, the difference between the measured and simulated values at 10 points was 0.02-7.55°C and the proportion was 0.04-16.6%.

3.3 Analysis of the simulation results before and after lawns were planted

Typically, after lawns were planted, the temperature of the bricked ground in Fuling Mausoleum was lower than that before lawns were planted at 10:00, 12:00 and 14:00.

Comparison of the simulated temperature curves before and after lawns were planted showed that the temperature of the bricked ground in front of Stele Pavilion at 10:00 decreased by 5.30–6.67°C after lawns were planted, a decrease of 9.17%–11.24% (Fig. 8). The temperature of the bricked ground in front of Long'en Gate decreased by 6.0°C after lawns were planted, a decrease of 11.85%. The bricked ground temperature in front of Long'en Hall decreased by 9.77–18.20°C after lawns were planted, a decrease of 16.86%–26.45%. Comparison of the simulated temperature curves before and after lawns were planted showed that the temperature of the bricked ground in front of Stele Pavilion at 12:00 decreased by 2.62–4.19°C after lawns were planted, a decrease of 4.08%–6.40% (Fig. 9). The temperature of the bricked ground in front of Long'en Gate decreased by 0.02–1.55°C after lawns were planted, a decrease of 0.04%–2.57%. The bricked ground temperature in front of Long'en Hall decreased by 0.90–3.38°C after lawns were planted, a decrease of 1.60%–5.93%. Comparison of the simulated temperature curves before and after lawns were planted showed that the temperature of the bricked ground in front of Stele Pavilion at 14:00 decreased by 2.69–4.26°C after lawns were planted, a decrease of 3.91%–6.09% (Fig. 10). The temperature of the bricked ground in front of Long'en Gate decreased by 1.56–9.40°C after lawns were planted, a decrease of 2.68%–14.75%. The bricked ground temperature in front of Long'en Hall decreased by 11.47–17.54°C after lawns were planted, a decrease of 17.56%–24.20%. The temperature of some measured points had increased because of the effect of airflow vortices. In air vortices, the heat could not be taken away in time, which had increased the bricked ground temperature.

3.4 Comparison and analysis of different wind speeds and relative humidity

According to the comparison of actual measurement and simulation data, the difference between the actual measurement and the simulation at Fuling Mausoleum was smallest at 14:00 and the simulation data were the closest to the actual measurement data. In this study, the simulation parameters of wind speed and relative humidity at 14:00 were changed to study the influence of different results on the thermal environment and microclimate. Fig. 11(a)–(c) present the wind speed cloud diagrams in the vertical direction of the central axis of Fuling Mausoleum at 10:00, 12:00, and 14:00. Fig. 11(d)–(f) present the relative humidity cloud diagrams in the vertical direction of the central axis of Fuling Mausoleum at 10:00, 12:00, and 14:00.

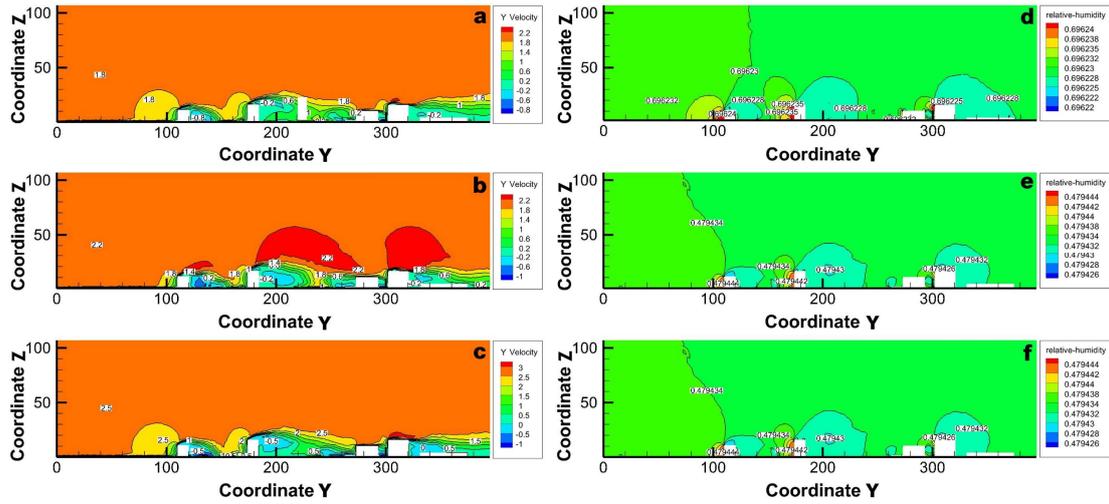


Fig.11 (a-c) Wind speed cloud diagrams in the vertical direction of the central axis of Fuling Mausoleum at (a) 10:00, (b) 12:00, and (c) 14:00. (d-f) Relative humidity cloud diagrams in the vertical direction of the central axis of Fuling Mausoleum at (a) 10:00, (e) 12:00, and (f) 14:00.

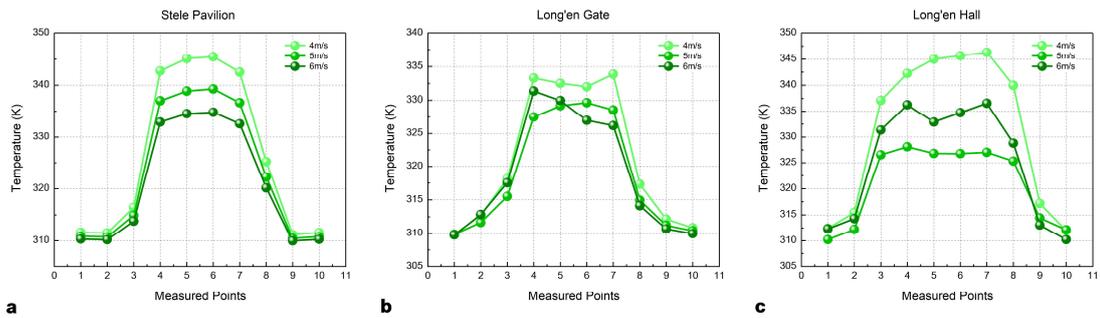


Fig.12 Comparison of simulation results at different wind speeds at (a) Stele Pavilion, (b) Long'en Gate, and (c) Long'en Hall.

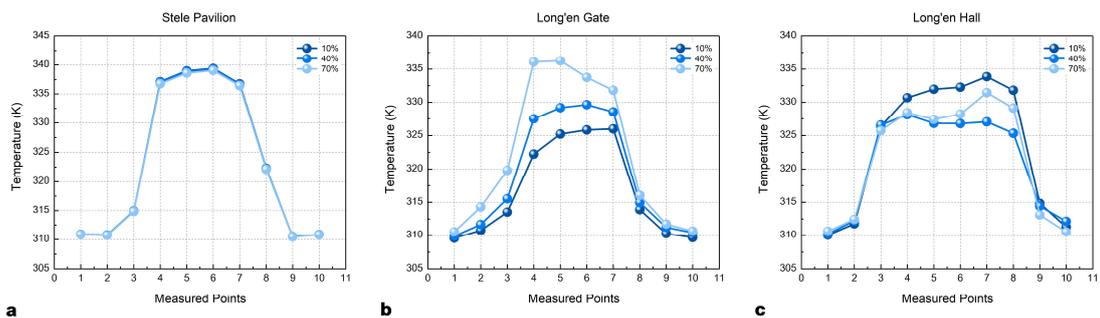


Fig.13 Comparison of simulation results at different relative humidity at (a) Stele Pavilion, (b) Long'en Gate, and (c) Long'en Hall.

Typically, as the wind speed increased, the ground temperature dropped. If the building was blocked by other walls, some of the measured points may be affected by airflow vortexes. Fig. 12(a)–(c) show temperature comparison diagrams of Stele Pavilion, Long'en Gate, and Long'en Hall with different wind speed at 14:00. We found

that after lawns were planted, with a wind speed of 5m/s compared with 4m/s, the temperature of the bricked ground in front of Stele Pavilion decreased by 5.72–6.24°C, a decrease of 8.21%–8.67%; the temperature of the bricked ground in front of Long'en Gate increased by 2.37–5.83°C, an increase of 4.03%–9.70%; and the temperature of the bricked ground in front of Long'en Hall decreased by 14.17–19.27°C, a decrease of 20.50%–26.34%. Compared with a wind speed of 5m/s, at a wind speed of 6m/s, the temperature of the bricked ground in front of Stele Pavilion decreased by 4.06–4.44°C, a decrease of 6.39%–6.71%; the bricked ground temperature in front of Long'en Gate decreased by 2.35–2.65°C, a decrease of 4.24%–4.70%; and the temperature of bricked ground in front of Long'en Hall increased by 6.10–9.53°C, an increase of 11.37%–17.69%.

Similar to the relative humidity, as the relative humidity increased, the ground temperature dropped. If the building was blocked by other walls, the wind speed will decrease and the temperature of the ground will increase when the relative humidity increases. Fig. 13(a)–(c) show the temperature comparison diagrams of Stele Pavilion, Long'en Gate, and Long'en Hall with different relative humidity at 14:00. We found that compared with lawns planted at 10% relative humidity, after lawns were planted at 40% relative humidity, the temperature of the tiled ground in front of Stele Pavilion decreased by 0.08–0.11°C, a decrease of 0.12%–0.17%; the temperature of the bricked ground in front of Long'en Gate increased by 2.55–5.25°C, an increase of 4.83%–10.69%; and the temperature of the bricked ground in front of Long'en Hall decreased by 2.57–6.82°C, a decrease of 4.47%–11.23%. At 70% relative humidity instead of 40% relative humidity, the temperature of the bricked ground in front of Stele Pavilion decreased by 0.21–0.28°C, a decrease of 0.34%–0.43%; the temperature of the bricked ground in front of Long'en Gate increased by 3.27–8.62°C, an increase of 5.91%–15.86%; and the temperature of the bricked ground in front of Long'en Hall increased by 0.33–4.40°C, an increase of 0.59%–8.17%.

3.5 Actual measurement of microclimate with the human thermal comfort index value.

Temperature is an important factor affecting human comfort and physical health. In the process of environment creation, it is essential that using vegetation to reduce air temperature and provide an excellent and suitable temperature environment for humans and the protection of architectural heritage (Fig. 14) [29]. At present, the most popular outdoor environmental evaluation indicators in China are the standard sufficient temperature and WBGT. The standard effective temperature index is used to evaluate the comfort of the environment (Table 5) [37] and the WBGT index is used to measure the safety of the thermal environment (Table 6) [38]. The project team members measured the air temperature, black bulb temperature, and WBGT values at five-time points (Table 7).

The human thermal comfort indexes in Table 5 and 6 and the measured results in Table 7 show that at 10:00 as solar radiation illuminance increased, the air temperature gradually increased. At this time, the black bulb temperature value of the environment

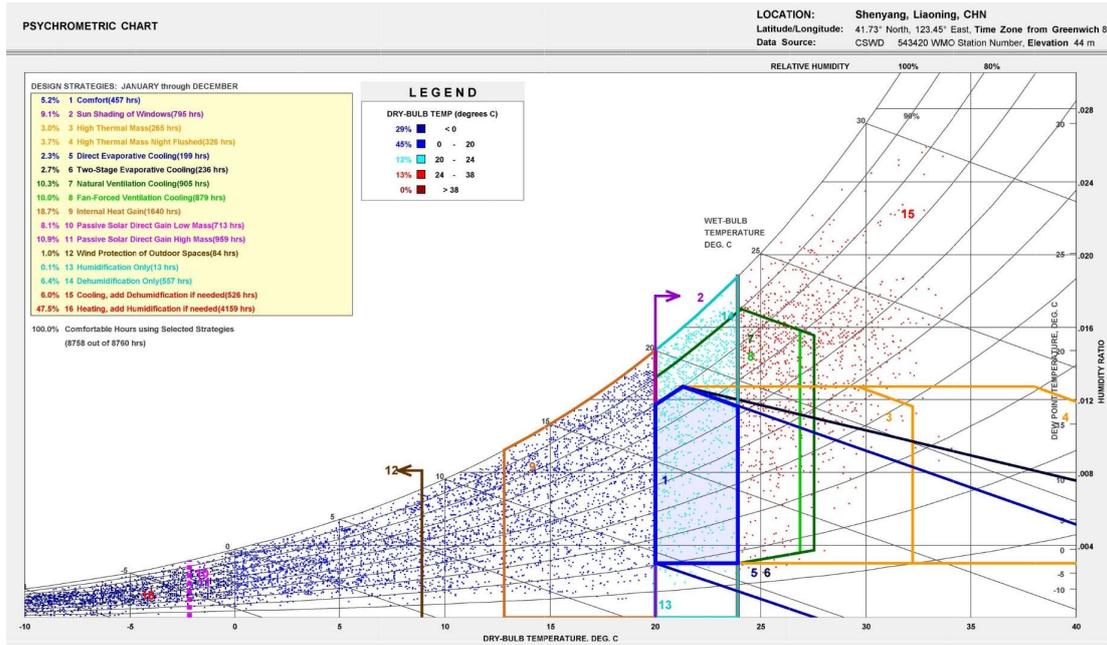


Fig.14 Psychrometric chart.

was 27.7°C, between 25.6 and 30°C, and the WBGT index was 23.3°C, between 18 and 24°C, indicating a “warm” thermal sensation range. At 12:00, as a result of intense solar radiation, the ground accumulated a considerable amount of heat. The black bulb temperature measured was 36.7°C and WBGT measured was 27.8°C. The thermal comfort index was in the “hot” thermal sensation zone. At 14:00, solar radiation was the strongest. The black bulb temperature measured was 39.6°C and WBGT measured was 29.7°C. In these cases, the environment was “hot” or “very hot”.

The main influences of outdoor environmental parameters on human thermal perception are temperature, humidity, solar radiation, and wind speed. Comparing the actual measurement with numerical simulation results, the thermal comfort of the investigation environment was calculated. The numerical simulation results were very close to the actual measurement data (Fig. 15).

Table 5 Standard effective temperature index [37]

Thermal comfort index	Comfortable	Slightly warmer	Slightly hotter	Hot	Very hot
Standard effective temperature (°C)	22.2-25.6	25.6-30	30-34.5	34.5-37.5	≥37.5

Table 6 WBGT thermal comfort index [38]

WBGT Index	Comfortable	warm	Hot	Very hot	Extremely hot
WBGT (°C)	<18	18-24	24-28	28-30	>30

Table 7 Real-time measurement of WBGT and black bulb temperature

Time (Hour)	Air temperature (°C)	black bulb temperature (°C)	WBGT temperature (°C)
10	26.1	27.7	23.3
11	29	34.8	25.2
12	31.4	36.7	27.8
13	31.6	37.7	28.5
14	33.7	39.6	29.7

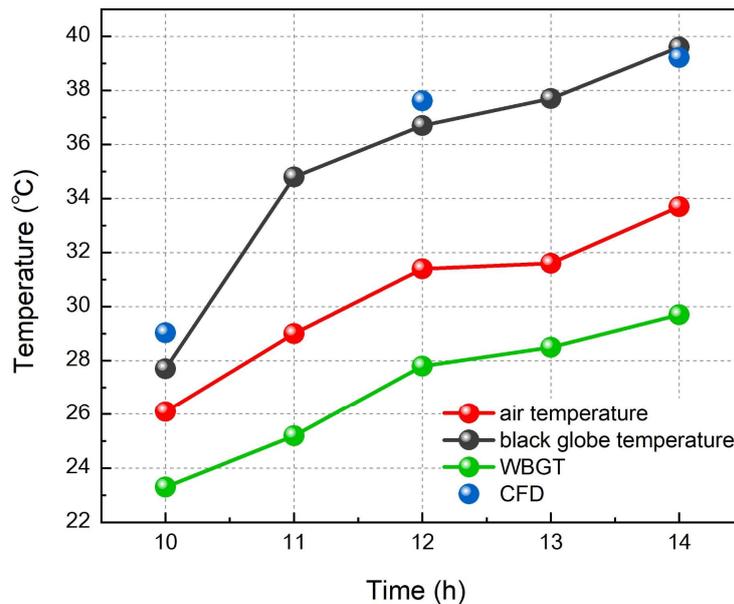


Fig.15 Numerical simulation results were very close to the actual measurement data.

4. Conclusions

The aims of this study were to compare measurement data and simulation results before and after planting grassland, compare the simulation results based on different wind speeds and relative humidity, and compare the actual measurements of the microclimate using the human thermal comfort index value, to reduce the damage to heritage sites caused by the heat island effect. The results of this research can be applied to the thermal environment and thermal comfort research of other heritage sites. The following conclusions were drawn from this study.

(1) Because lawns and soil can cool the air through evaporation and the soil has a significant radiation absorption coefficient, it can also absorb more heat radiation and generate higher temperatures locally. The greening of the surrounding environment can affect the bricked ground and lead to a specific cooling effect.

(2) The consistency of the difference between the actual measurement and the CFD simulation results indicates that the selection of simulation parameters was reasonable and could accurately reflect the internal temperature field distribution at Fuling

Mausoleum. The CFD simulation was able to predict the temperature of the surrounding environment at heritage sites.

(3) The temperature of the bricked ground at Fuling Mausoleum after lawns were planted was lower than that before lawns were planted. As the wind speed and relative humidity increased, the ground temperature dropped. If the building was blocked by other walls, the temperature of some measured points may be affected by airflow vortexes and the temperature of the bricked ground will increase when the wind speed increases.

(4) The main influences of outdoor environmental parameters on human thermal perception are temperature, humidity, solar radiation, and wind speed. The actual measurement data were very close to the numerical simulation results.

Abbreviations

CFD: computational fluid dynamics; WBGT: wet bulb globe temperature.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Written informed consent for publication was obtained from all participants.

Availability of data and materials

The data is available within the article.

Competing interests

The authors declare that they have no competing interests.

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Author Contributions

X.W., P.L. and G.X. contributed equally to this work.

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Not applicable.

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Figures

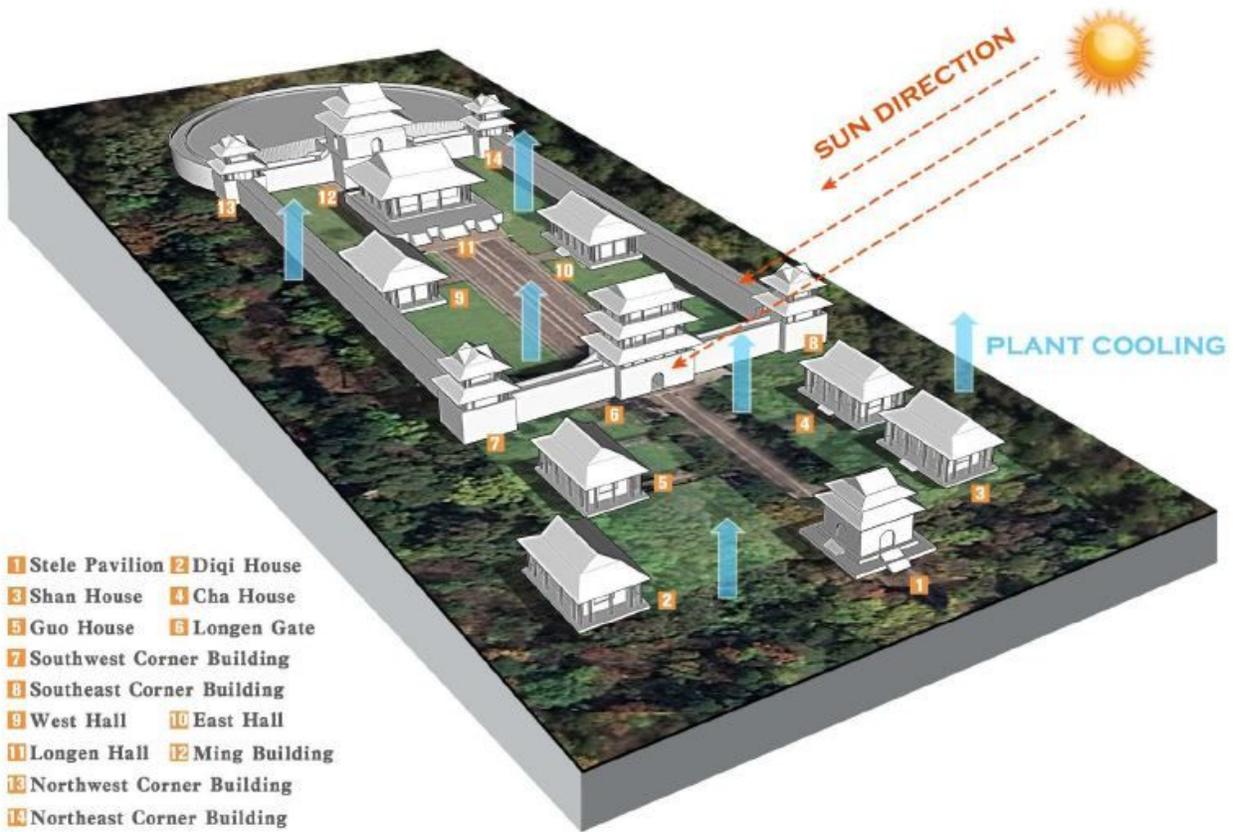


Figure 1

The environment surrounding Fuling Mausoleum (white is the CFD simulation model).



Figure 2

Measuring instruments: (a) black bulb thermometer, (b) anemometer, (c) heat flux sensor (photos by Xiaoyu Wang).

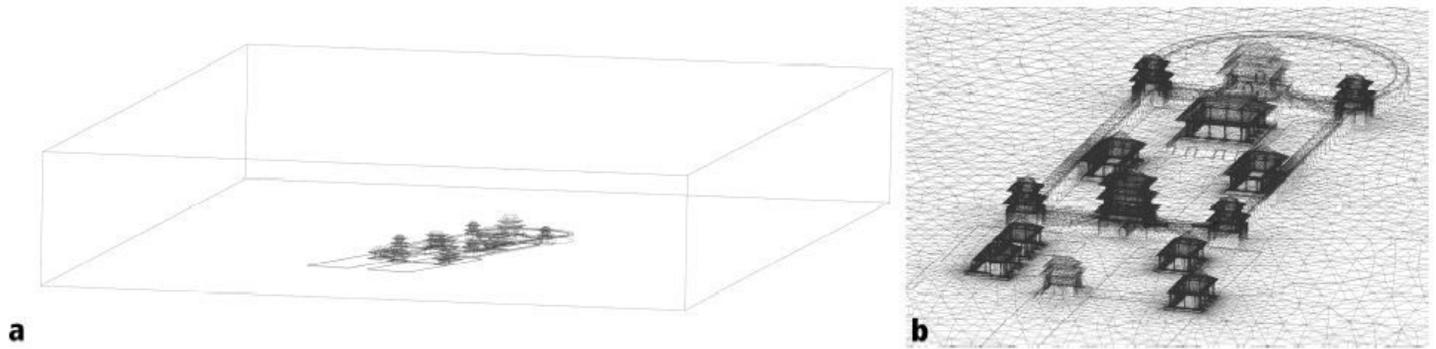


Figure 3

(a) General views of the computational domain (geometry and mesh) for Fuling Mausoleum. (b) Detail of the mesh refinement with tetrahedral elements.

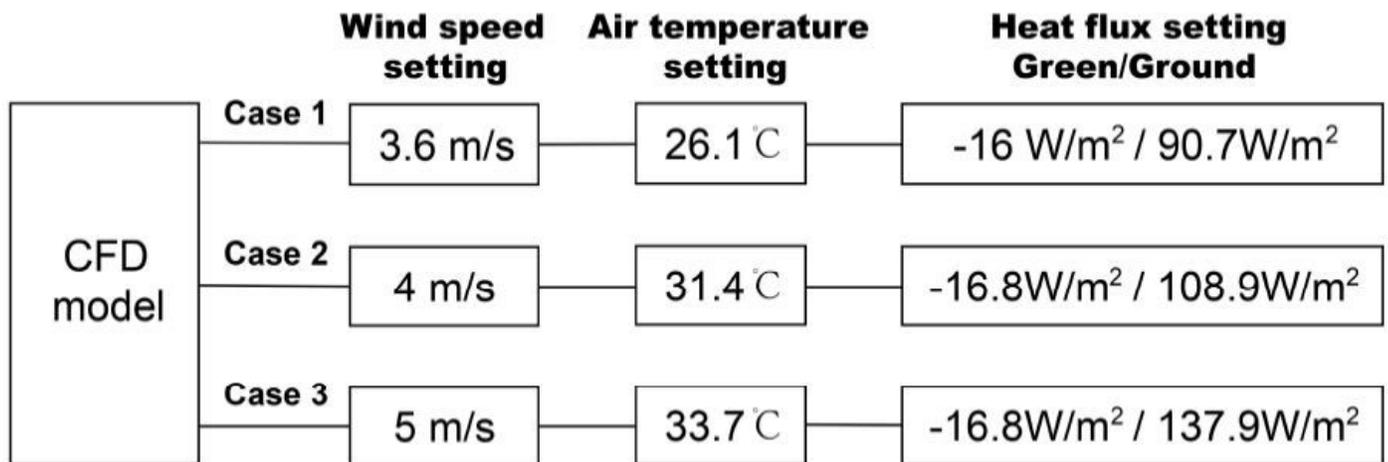


Figure 4

Settings of the specific numerical simulation scheme.

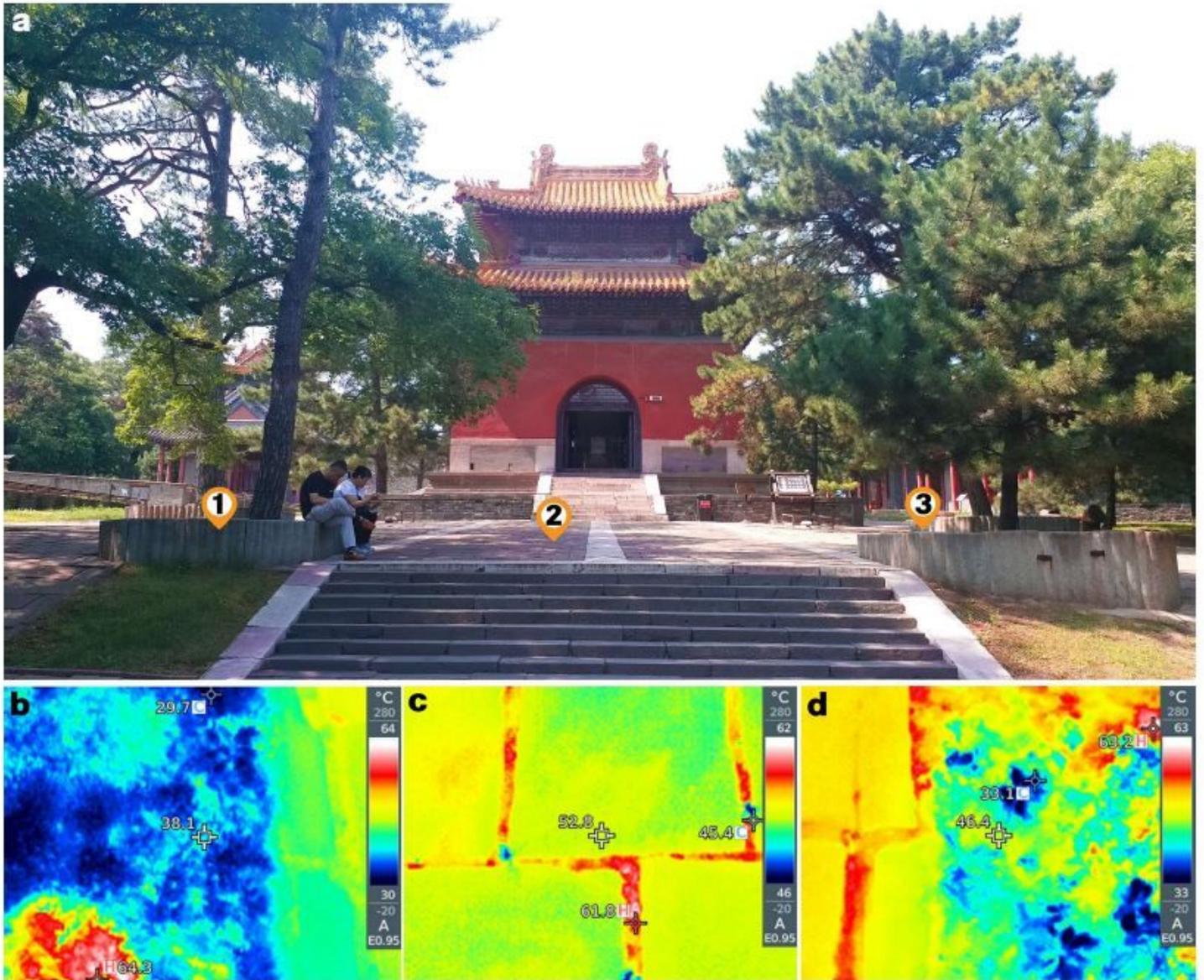


Figure 5

Photo and infrared images of the site in front of Stele Pavilion: (a) photo of the site and overhead of (b) lawns to the left, (c) bricked ground, (d) lawns to the right (photo by Xiaoyu Wang).

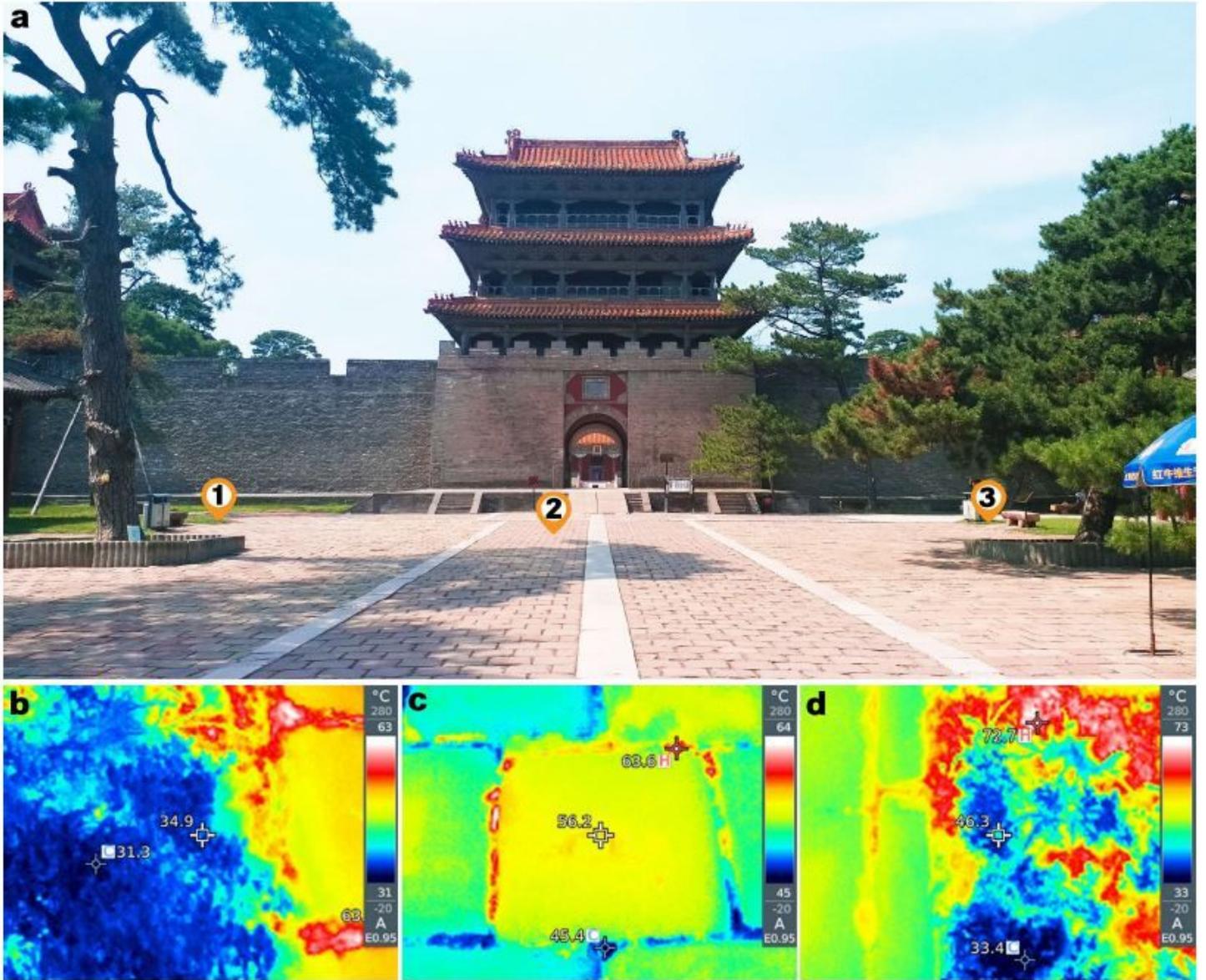


Figure 6

Photo and infrared images of the site in front of Long'en Gate: (a) photo of the site and overhead of (b) lawns to the left, (c) bricked ground, (d) lawns to the right (photo by Xiaoyu Wang).

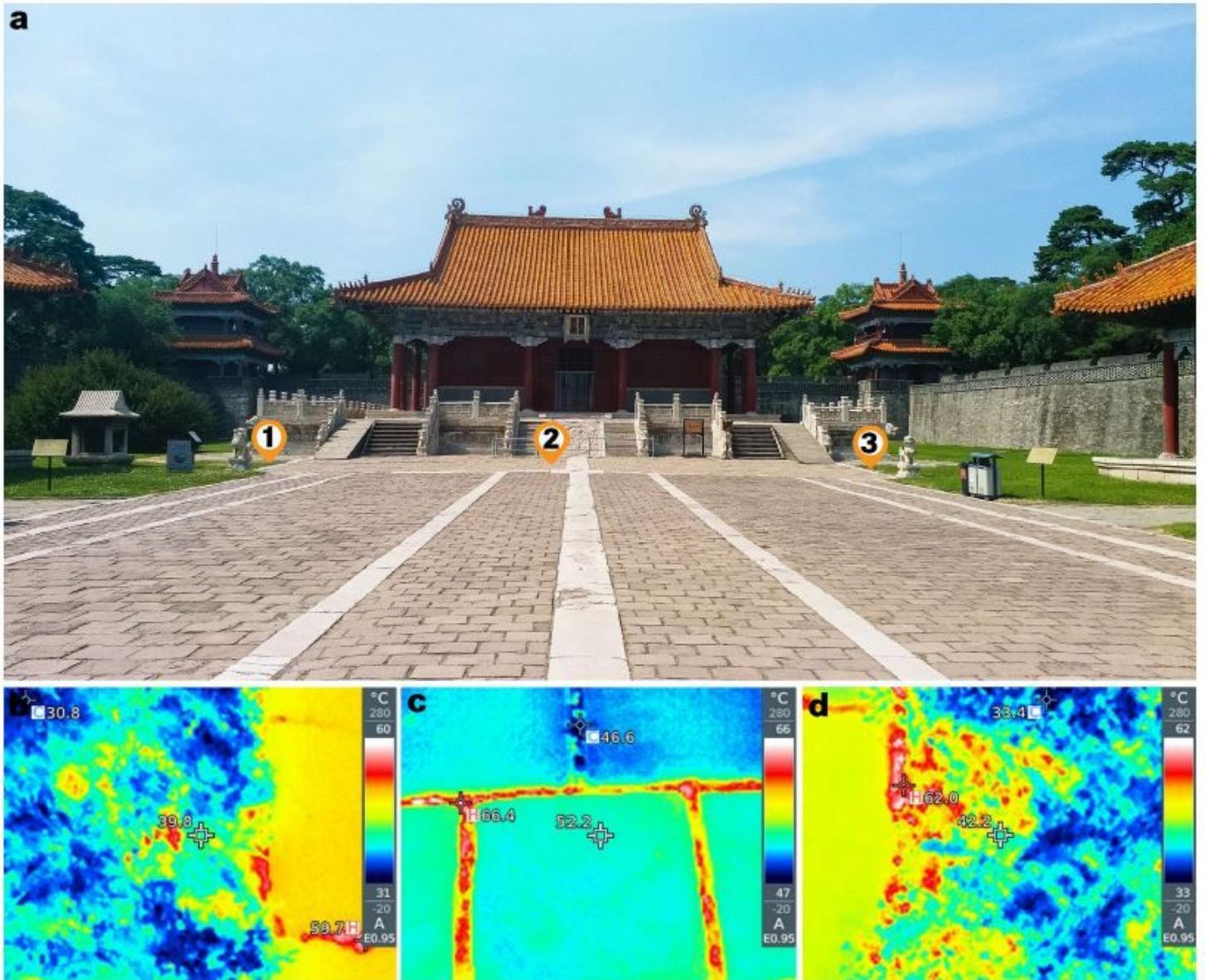


Figure 7

Photo and infrared images of the site in front of Long'en Hall: (a) photo of the site and overhead of (b) lawns to the left, (c) bricked ground, (d) lawns to the right (photo by Xiaoyu Wang).

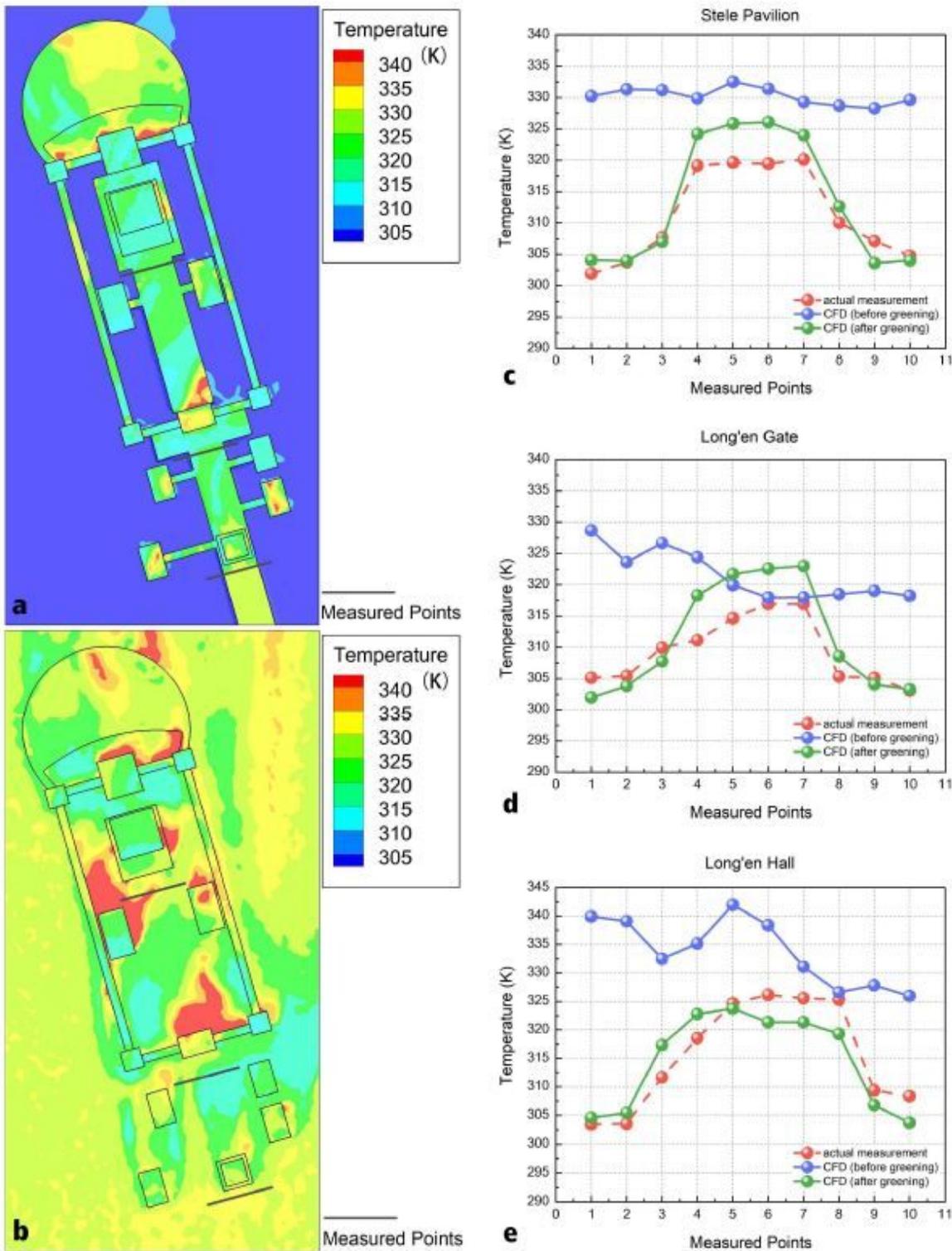


Figure 8

Temperature cloud diagrams and measurement point locations of the numerical simulation at 10:00 (a) after lawns were planted and (b) before lawns were planted. (c-e) Comparison of actual measurement with simulation results in front of Stele Pavilion at 10:00 (c) in front of Stele Pavilion, (d) in front of Long'en Gate, and (e) in front of Long'en Hall.

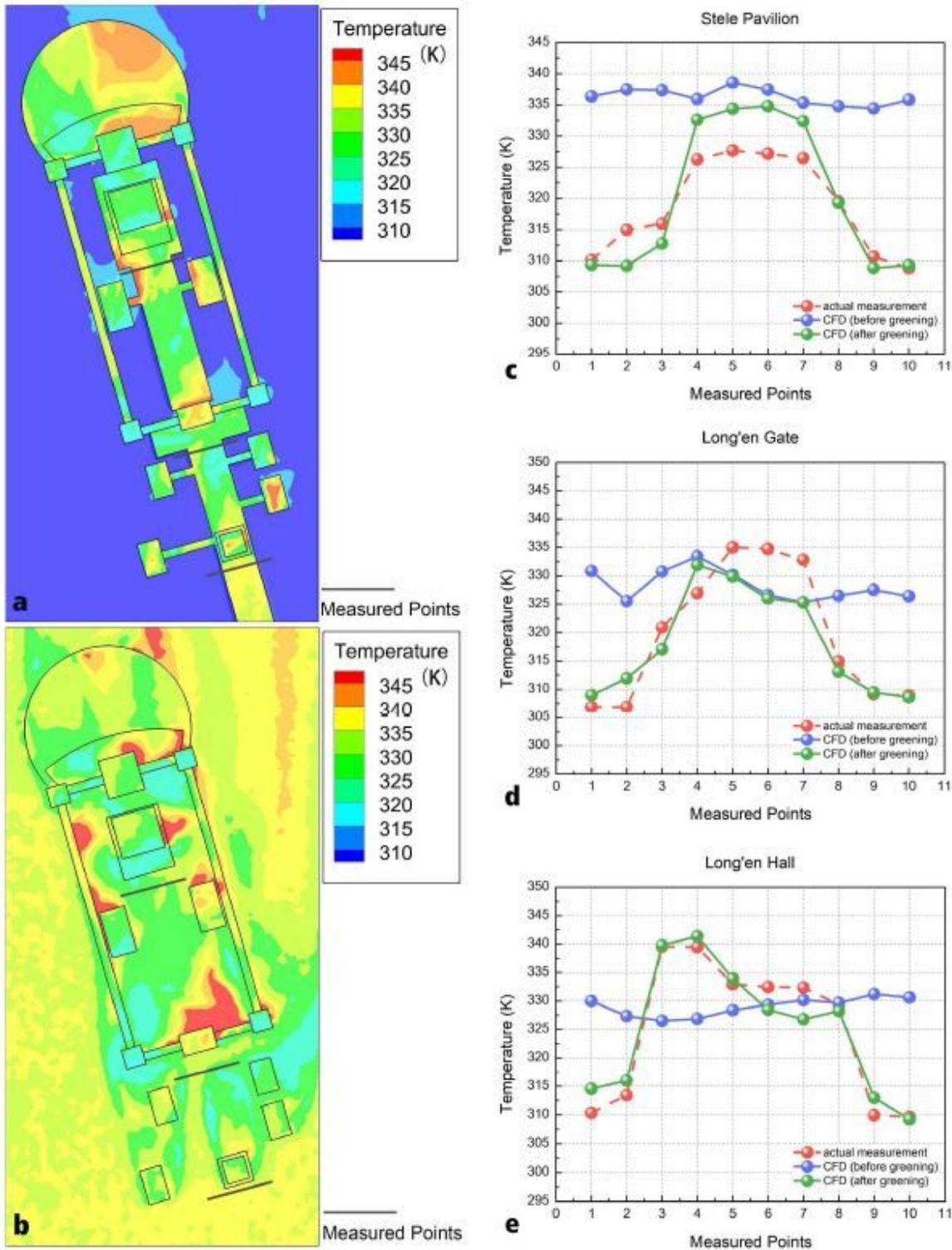


Figure 9

Temperature cloud diagrams and measurement point locations of the numerical simulation at 12:00 (a) after lawns were planted and (b) before lawns were planted. (c-e) Comparison of actual measurement with simulation results in front of Stele Pavilion at 12:00 (c) in front of Stele Pavilion, (d) in front of Long'en Gate, and (e) in front of Long'en Hall.

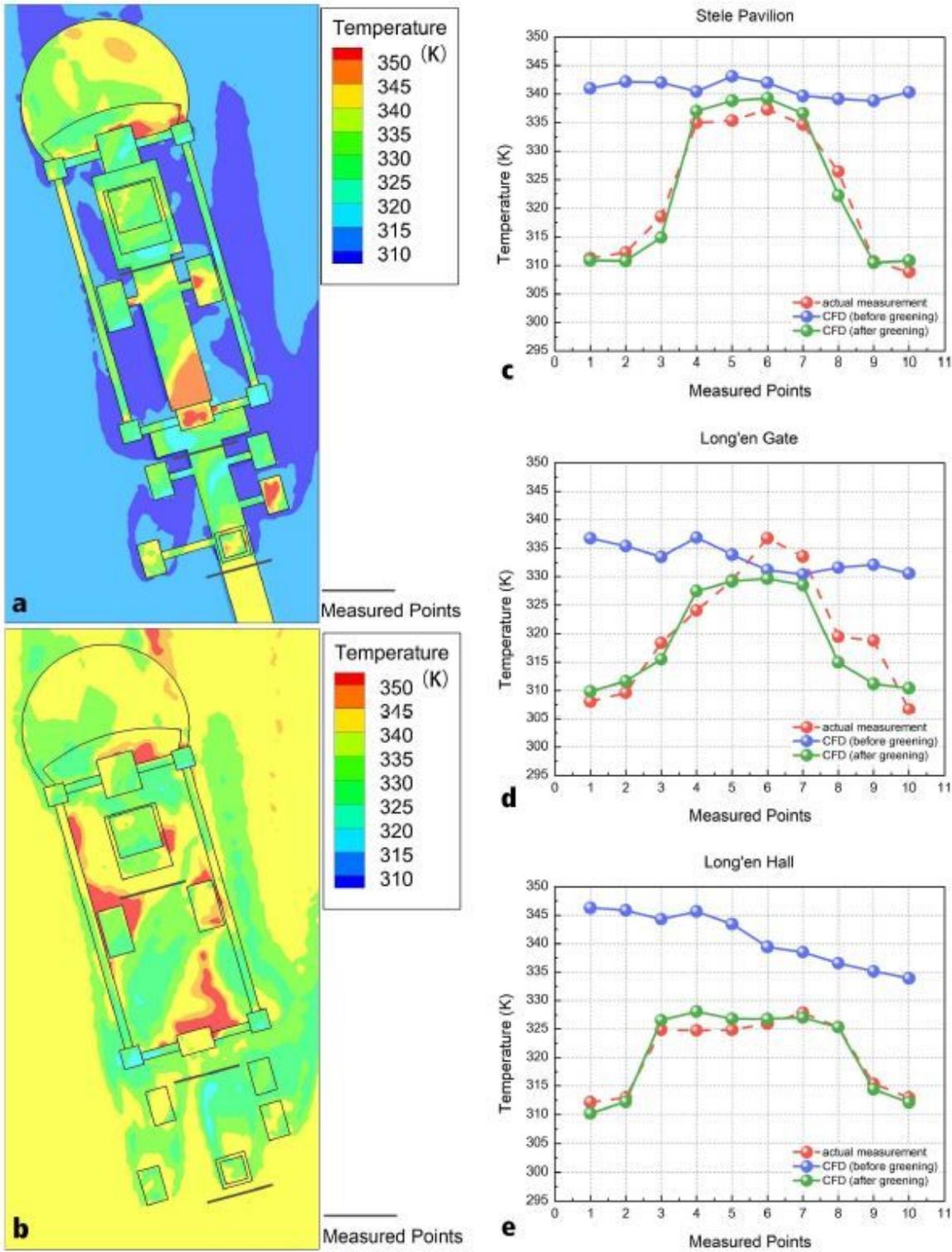


Figure 10

Temperature cloud diagrams and measurement point locations of the numerical simulation at 14:00 (a) after lawns were planted and (b) before lawns were planted. (c-e) Comparison of actual measurement with simulation results in front of Stele Pavilion at 14:00 (c) in front of Stele Pavilion, (d) in front of Long'en Gate, and (e) in front of Long'en Hall.

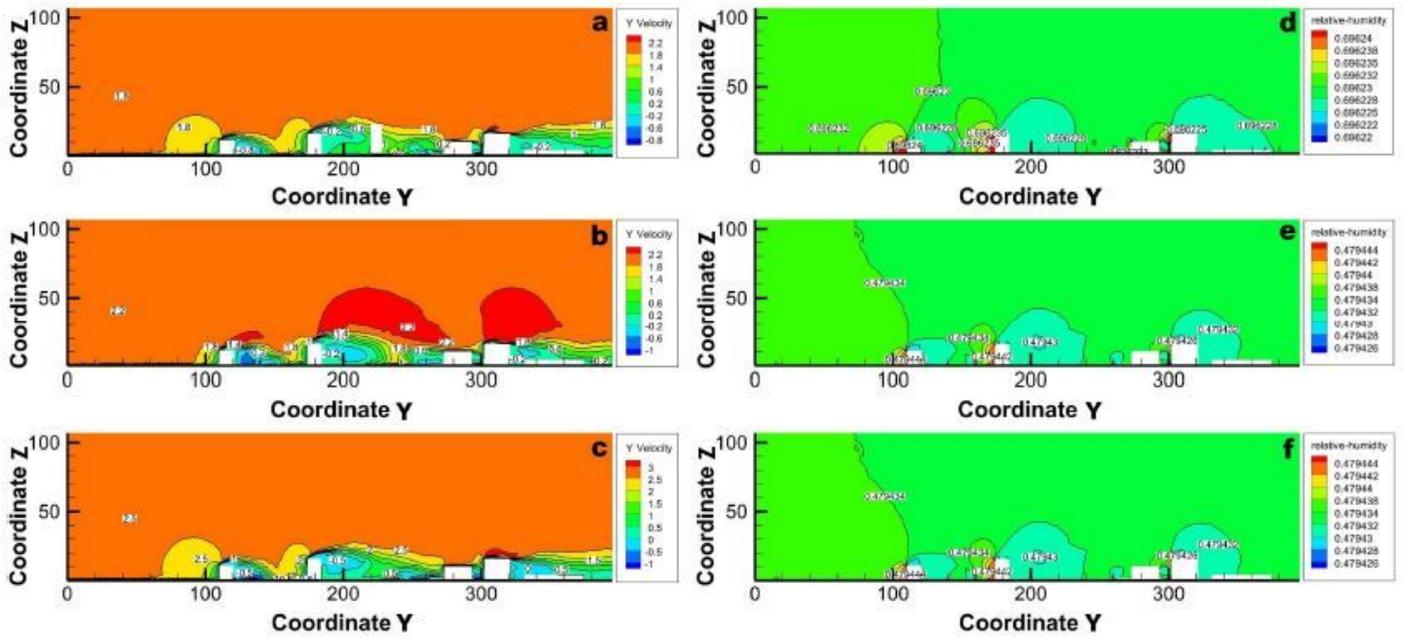


Figure 11

(a-c) Wind speed cloud diagrams in the vertical direction of the central axis of Fuling Mausoleum at (a) 10:00, (b) 12:00, and (c) 14:00. (d-f) Relative humidity cloud diagrams in the vertical direction of the central axis of Fuling Mausoleum at (a) 10:00, (e) 12:00, and (f) 14:00.

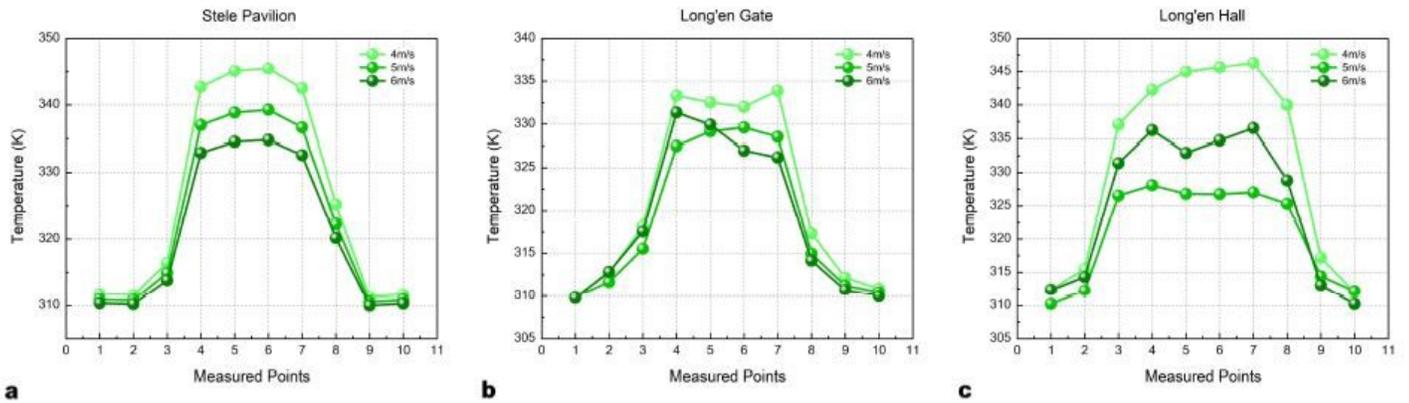


Figure 12

Comparison of simulation results at different wind speeds at (a) Stele Pavilion, (b) Long'en Gate, and (c) Long'en Hall.

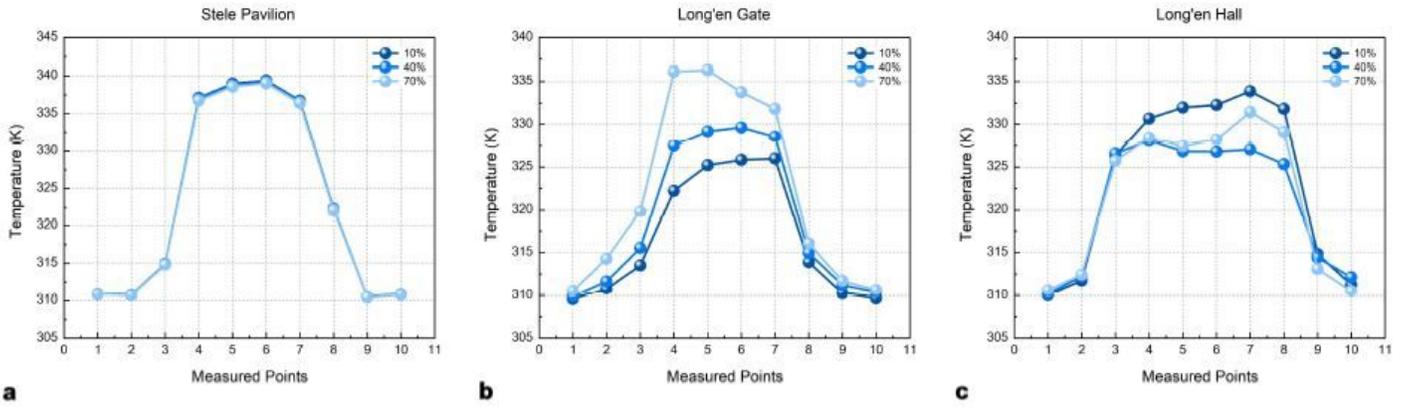


Figure 13

Comparison of simulation results at different relative humidity at (a) Stele Pavilion, (b) Long'en Gate, and (c) Long'en Hall.

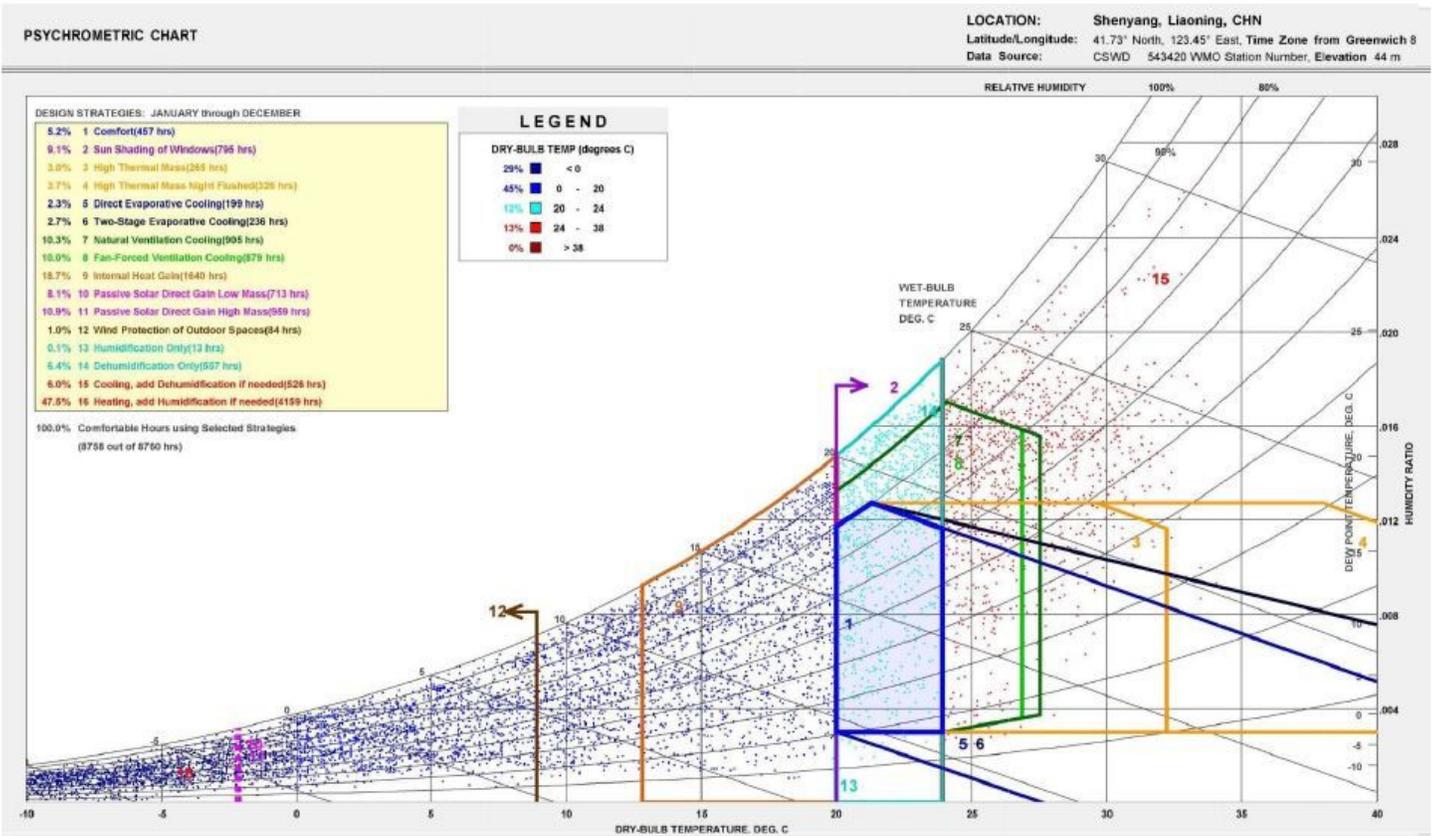


Figure 14

Psychrometric chart.

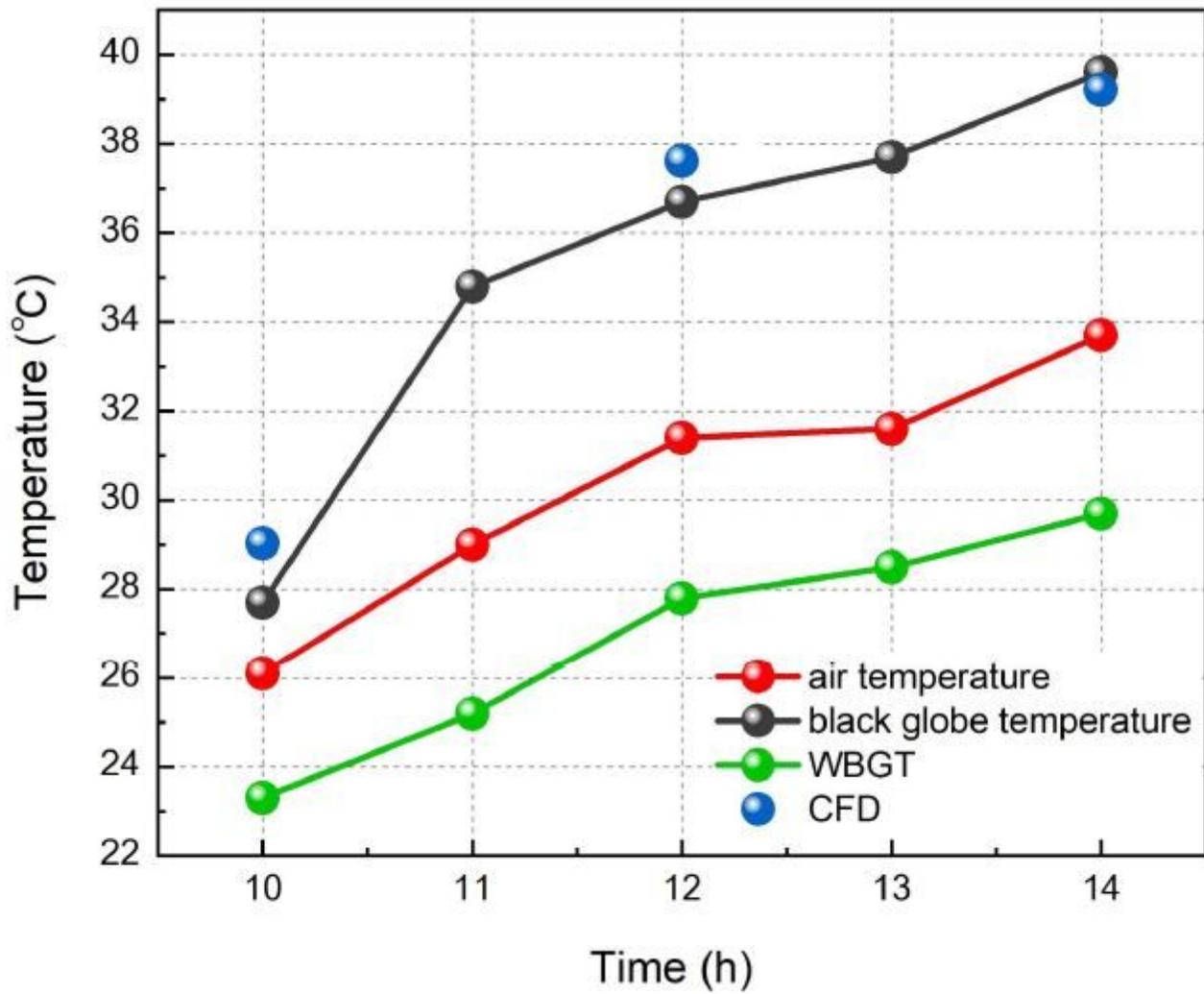


Figure 15

Numerical simulation results were very close to the actual measurement data.