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Research on Thermal Environment in Dunhuang Mogao Grottoes

Ruihua Shang*[a,b], Zengfeng Yan[b], Xudong Wang[c,d], Zhengmo Zhang[c], Jiangli Wang[b,e], Xiawei Fan[b]

[a]School of Architecture and Engineering, Taiyuan Univ. of Tech., Taiyuan 030000, China
[b]School of Architecture, Xi’an Univ. of Arch. & Tech., Xi’an 710055, China
[c]Conservation Institute, Dunhuang Academy, Dunhuang 736200 China
[d]School of Engineering and Mechanics, Lanzhou Univ., Lanzhou 730000 China
[e]School of architecture and engineering, Henan Univ. of Scie. & Tech., Luoyang 471003, China
shangruihua@126.com

In order to compare with the influence of different underlying surfaces on thermal environment, the software Fluent is used to simulate the thermal environment of Dunhuang Mogao Grottoes. The results show that (1) the warming effect at 12:00 of terrain raises 1.9°C; (2) one of the bare lands declines 0.3°C; (3) one of the trees without considering heat-storage and transpiration reduces the air temperature in shadow regions but increases in square regions; (4) one of the trees with considering heat-storage reduces 0.17°C. It indicates that about 82.5% heat reduces caused by transpiration effect. It’s thus concluded that the terrain of Mogao Grottoes increases the air temperature, while different underlying surfaces and trees reduce that.

1. Introduction

“Management Approach of National Archaeological Heritage Park (Trial)” and “Assessment Rules of National Archaeological Heritage Park (Trial)” were issued by China’s Administration of Cultural Heritage on December 17, 2009. In October 2010 and January 2013, there are 24 national archaeological site parks have been selected. Relic protection and utilization are no longer a useless slogan but a plan into practice. China’s Archaeological Heritage Park, as an important relic protection and utilization model, is a significant symbol for the protection of China’s Heritage site. The oasis landscape of Mogao Grottoes should also be evaluated.
The special terrain and vegetation form a large range of climate, while the real affective landscape is the micro-climate enclosed with cliffs, forest belts and squares (Shang et al., 2016). As a typical arid region, the micro-climate affected by the topographies, water and vegetation of Mogao Grottoes, is obviously different from the macro-climate day and night. Therefore, the regulating effect of micro-climate is greater than other regions. The building in Mogao Grottoes is cave, with a single opening to air exchanges. Different climate environment is shown in Figure1.

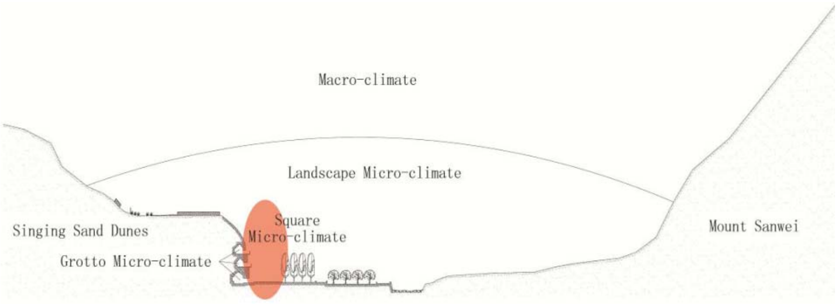

Figure 1: Relationship among Different Climate Environment in Mogao Grottoes.

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Vegetation affects the wind and thermal environment greater than other non-arid regions. Experts have proved that the outdoor micro-climate environment influences indoor physical environment in different levels (Shang et al., 2014; Shang et al., 2017). Wang Jiangli pointed out that both heat pressing and hot pressure affected the inner micro-airflow and the cultural relics' environment (Wang et al., 2016; Wang and Yan, 2014)
The cultural relics in Mogao Grottoes are murals and clay sculptures. The protection work requires the dry climate. Ao Yinhuan calculated relative parameters, just like the daily reflectivity mean value of Gobi, desert and oasis, soil heat flux of 5cm and 20cm, as well as soil thermal conductivity of 5cm. They provided an important basis for the simulation parameters (Ao et al., 2013). Regardless of the water infiltration, Li Hongshou didn't mention the proportion of these five factors' reflection on the thermal environment, although he pointed out the reduced value of maximum daily temperature is no less than 3.87°C (Li, 2006). Shang Ruihua could not fully and intuitively explain the effect of greening on the thermal environment for its large research scale and little test points, though she pointed out thermal reflection features by testing different underlying surfaces and heights (Shang et al., 2017; Shang et al., 2016). Stepben didn't analyze the mechanism structure of vegetation "umbrella" which was a wet structural system (Lesiuk and Wen, 1985).
According to the insufficient of the above researches, the software Fluent is used to simulate different underlying surfaces' reflection of the thermal environment. With the method of increasing the surface factors, several simulations are carried out to find out the influence degree of different underlying surface factors.

2. Simulation procedure

2.1 Simulation scale

Mogao Grottoes is at an altitude between 1320 m and 1380 m, which is lower about 100 m than Singing Sand Dunes and about 600 m than the peak of Mount Sanwei. The result indicates that the quantity of water resources and its utilization determine the scale of oasis. Li Hongshou pointed out that the shortage period of the water, the timing is from the appearance of defoliation, was up to 85 days, accounting for 1/3 of the water supply time (Li, 2005). It can be seen that the existing Mogao Oasis is approaching the upper limit of water resources. That means the scale of oasis is inadvisable expanded. In order to form a grid and reserve terrain by Fluent, we need to simplify the model. The greening range only contains the scenic and official greening, but not the greening above caves. The simulation range is East-West 1000 m and South-North 2800 m.

2.2 Parameter settings

Table 1: Physical Parameters of Underlying Surface Materials

Type	R_D	R_C	c	λ	ρ	λ_T
	-	-	$J/(kg\cdot°C)$	$W/(m\cdot°C)$	kg/m^3	$W/(m\cdot°C)$
Wall (aerated concrete)	0.35	0.9	1050	0.22	700	-
Roof (reinforced concrete)	0.35	0.9	920	1.74	2500	-
Pavement and rigid pavement	0.25	0.9	1680	1.05	2100	-
Soil	Gobi 0.223 Desert 0.188 Bare land 0.2	0.9	1465	0.42	950	0.193 0.317 -
Water	-	0.9	4182	0.6	998.2	-
Tree (shadow)	0.172	-	2310	0.173	700	0.374
Tree (shadow & heat-storage)	0.6	0.95	5	0.06	950	-
Atmosphere	-	-	1006.43	0.0242	1.225	-

This paper applied AutoCAD to build a 3D model, through Gambit to get meshes and Fluent 6.3 to get parameters and the simulation. Relevant parameters are listed in Table 1. According to the query, the absorption and transmittance rate of bare lands' solar radiation are 0.2 and 0.55 respectively, and of the water are 0.05 and 0.5 respectively (Lesiuk and Wen, 1985). Two equation models of k-epsilon are chosen as a turbulence model, which solves each discrete equation by the rectification of pressure and velocity. The simulation condition takes meteorological data in front of Grotto 72 as the standard, picking each two hours between 8:00 and 18:00 on June 21, 2012. The data of air temperature is tested, and one of the dry temperatures and wet bulb temperatures is calculated by standards. This simulation ignores the transpiration of soils and vegetation. The wind environment is static, i.e. the wind speed is 0m/s. The mesh types in simulation are Tet/Hybrid and Tgrid, which can ensure the volume mesh size of buildings and other surfaces are no more than 3 m. The analysis indicates that the quality of this kind of meshing is high. The proportion of the distortion rate in bare lands is nearly 95.4% which takes the grid size less than 0.6, and that in trees is nearly 95.24%.

Table 2: Simulated Meteorological Parameters

2012.06.21	The square in front of caves				Open space above caves			
	Air temp.	Surface temp.	Wet bulb temp.	Sunshine	Air temp.	Surface temp.	Wet bulb temp.	Sunshine
	°C			W/m2	°C			W/m2
8:00	23.26	23.23	12.26	26.9	22.7	24.26	12.35	245
10:00	27.21	27.51	14.87	81.9	29.26	39.79	20.43	657
12:00	32.92	34.20	17.23	329.4	31.44	52.99	26.87	960
14:00	36.23	41.71	20.51	933.1	33.27	58.7	28.64	1071
16:00	34.44	35.56	17.75	183.1	34.23	58.42	28.25	785
18:00	33.84	34.02	16.39	59.4	34.26	51.4	24.24	613

The values of parameters in the table are tested by the annual meteorological station, and wet bulb temperature is calculated by the chart of dry bulb temperature and relative humidity.

Physical parameters of underlying surfaces are listed in Table 2. The signal of R_D represents short wave reflectivity. R_C means long wave emissivity. *c* is specific heat capacity, *J/(kg·°C)*. *λ* is thermal conductivity, *W/(m·°C)*. *ρ* is density, kg/m^3. λ_T means soil thermal conductivity, *W/(m·°C)*.
The specimens with a size of 150 mm×150 mm×550 mm are used for pore pressure tests. After casting, all specimens are stored in a standard curing room of concrete with moulds for 24 hours. Thereafter, they are de-moulded, subjected to 20 °C water and cured for 28 days. The initial moisture of specimens is between 4% and 5% by mass.

3. Scenarios and analysis

In this section, four scenarios are set up in Table 3.
Scenario A is a sand simulation. That means all underlying surfaces are gritstone except Daquan River. The result of simulation is a reference of temperature which represents the terrain influence of Mogao Grottoes.
Scenario B is a bare land simulation. That means different underlying surfaces are taken into consideration but no trees in greening. It includes the influence of terrain and different underlying surfaces on the temperature.
Scenario C is a tree (shadow) simulation. It only considers the shadow function of trees without the heat-storage and transpiration of trees and soils. In order to avoid leaves temperature deviating from the actual value, absorption rate of solar radiation is set to 0 and transmittance rate 0.75.
Scenario D is a tree (shadow & heat-storage) simulation. The quantity of the liquid water in the tree is above 80%-90%. Considering its heat storage is impossible when the material of trees is set to wood. The moisture content in the tree is dynamically stable, no matter whether or not the transpiration is carried out. It's tested that the surface temperature of leaves is lower 1.5 °C than the air temperature, and the air temperature under the canopy is lower 1.9 °C than the one in the canopy (Lin, 2004). The surface temperature of trees is set to the air temperature, which has little effect on the simulation results.

Table 3: Simulation Scenarios

Scenarios	Types of underlying surfaces
A Sand simulation	gritstone, water.
B Bare land simulation	gritstone, water, road, bare land, wall, roof.
C Tree (shadow) simulation	gritstone, water, road, bare land, wall, roof, tree (shadow) .
D Tree (shadow & heat-storage) simulation	gritstone, water, road, bare land, wall, roof, tree(shadow & heat-storage).

3.1 Scenario A & scenario B

Distributions of scenario A and scenario B on the surface temperature are shown in Figures 2 and 3. The simulation analysis results are as follows:
(1) In scenario A, the surface temperature of squares is obviously higher than that of mountains. The phenomenon is due to multi absorption of long wave radiation from the L-type valley terrain. It has increased the surface temperature of squares. It's proved that the more the temperature difference between inside and outdoor, the more conducive to the heat-pressing ventilation (Shang et al., 2016). It can be seen that the valley terrain of Mogao Grottoes, compared with the flat terrain, is conducive to its heat-pressing ventilation.
(2) In scenario B, the surface temperature of squares in front of caves with masonry materials is still higher than that of mountains. But compared with scenario A, the surface temperature and air temperature of

squares reduce 0.5°C and 0.3°C respectively, and of other hard pavements reduce 1.02°C and 0.13°C respectively. It can be seen that different underlying surfaces in Mogao Grottoes is beneficial to the improvement of climate environment.

(3) Taking mean values of the air temperature as references for these two simulations, the surface temperature of the northern cliff and the northern square is higher than that of the southern cliff and the southern square. However, in scenario A and scenario B, the air temperature of the northern square is higher 1.91 °C and 1.63°C than that of the southern square, respectively. The reason for this phenomenon is that the arc of the southern cliff is larger than that of the northern cliff, which makes the condition of ventilation and heat dissipation worse. It's easy to be heated in this area.

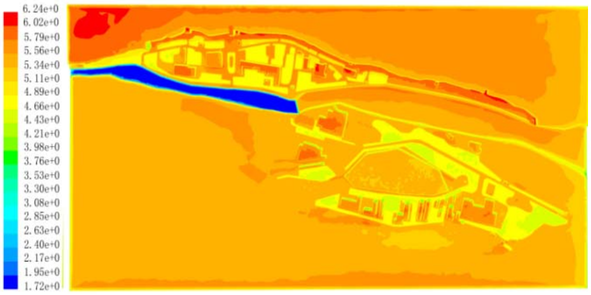

Figure 2: Distributions of Scenario A on Surface Temperature at 12:00

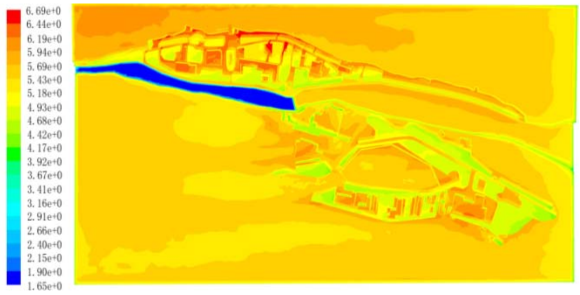

Figure 3: Distributions of Scenario B on Surface Temperature at 12:00

3.2 Scenario B & scenario C

Surface temperature analysis: Distribution of scenario C on the surface temperature is shown in Figure 4.

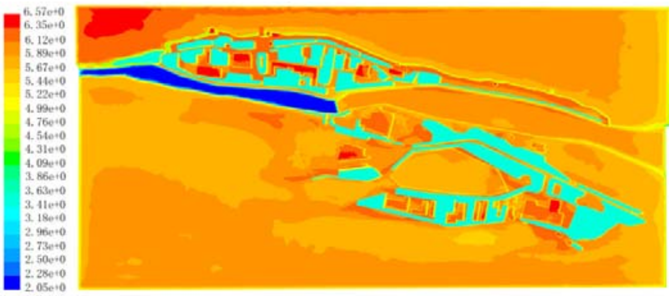

Figure 4: Distributions of Scenario C on Surface Temperature at 14:00

Air temperature analysis: The simulation analysis results are as follows:

(1) The forest belt reduces the air temperature of the northern square and rises the air temperature of the southern square. Before 16:00, compared with the air temperature of the northern square in scenario B, the decreased degree in scenario C is less than 0.1 °C. The air temperature of the southern square in scenario C is higher than that in scenario B. On one hand, it's due to the obstruction of ventilation and the poor capacity of heat dissipation. On the other hand, without considering the heat-storage and transpiration, the forest belt increases the absorption of long wave radiation, which caused a high temperature.

(2) Mean values of the air temperature in scenario C are higher than that in scenario B, and some parts are obviously at high temperatures, which form a bad thermal environment. That's because the weak ventilation, which is formed by the canyon terrain and the high density of planting trees in Mogao Grottoes, is unfavorable to the heat dissipation in the leeward area.

(3) The surface and air temperature under the tree shadow area are lower than that out of the tree shadow area. That's because the trees' overshadowing has a great influence on the surface and air temperature.

3.3 Scenario D

3.3.1 Surface temperature analysis

The simulation analysis results are as follows:

(1) Compared with the scenario B, the surface temperature of the square before 12:00 reduces 2.5°C in the scenario D, and one of the other squares and roads also reduce.

(2) Compared with the scenario C, the surface temperature of the square decreases between 12:00 and 16:00 in the scenario D.

3.3.2 Air temperature analysis

Mean values of the air temperature increment at the height of 1.5 m are listed in Table 4. The simulation analysis results are as follows:
(1) Compared with scenario B, air temperature mean values of the square at the height of 1.5 m at 12:00 and 16:00 reduce 0.17°C and 0.15°C, respectively.
(2) Compared with the scenario C, air temperature mean values of the square at the height of 1.5 m at 12:00 and 16:00 reduce 0.4°C and 0.42°C, respectively. It has a great relationship with the bad ventilation and heat dissipation for the leeward area.

Table 4: Mean Values of Air Temperature Increment at the Height of 1.5m

°C	8:00	10:00	12:00	14:00	16:00	18:00
$\overline{\Delta T_{Q1-L}}$	0.13	0.21	0.23	0.28	0.28	0.41
ΔT_{Q2-L}	-0.05	-0.09	-0.17	-0.09	-0.15	0.07

ΔT_{Q1-L} represents mean value of air temperature increment at the height of 1.5m by comparison of tree (shadow) simulation and scenario B; ΔT_{Q2-L} represents mean value of air temperature increment at the height of 1.5m by comparison of tree (shadow & heat-storage) simulation and scenario B.

3.4 Heat-island intensity analysis

In this paper, several criterions are chosen to judge whether the heat island intensity exceeds the standard 1.5 °C. Daily mean values of the heat-island intensity are listed in Table 5. The simulation analysis results are as follows:
(1) Daily mean values of the heat-island intensity in Mogao Grottoes change with the time. The value at 8:00 is the lowest and the maximum value at 14:00 is no more than 1.5 °C.
(2) The heat-island effect of the terrain in scenario A is up to 0.6 °C at 14:00. Different underlying surfaces in scenario B decrease the heat-island effect, compared with ΔT_s. The overshadowing effect in scenario C increases the heat-island effect, compared with ΔT_s and ΔT_L. Without considering the transpiration, the effect of overshadowing and heat-storage in scenario D reduce the heat-island effect, while the change of heat-island intensity is still represented by the oasis temperature higher than the terrain temperature.

Table 5: Daily Mean Values of Heat-Island intensity

°C	8:00	10:00	12:00	14:00	16:00	18:00
ΔT_s	-	-	0.58	0.6	0.51	-
ΔT_L	0.27	0.39	0.49	0.5	0.43	0.18
ΔT_{Q1}	0.26	0.52	0.64	0.68	0.59	0.4
ΔT_{Q2}	0.16	0.33	0.4	0.45	0.34	0.2

ΔT_s represents daily mean value of heat-island intensity of scenario A; ΔT_L represents daily mean value of heat-island intensity of scenario B; ΔT_{Q1} represents daily mean value of heat-island intensity of scenario C; ΔT_{Q2} represents daily mean value of heat-island intensity of scenario D.

The above simulations are different from the actual situation. But the simulation results still can explain related problems for increasing elements of simulations step by step. Without considering the transpiration, the effect of terrain, different underlying surfaces, overshadowing and heat-storage by trees is to reduce the daily maximum value of the air temperature 0.6°C. Some researches show that 59% garden water usage in Mogao Grottoes, about 4917 mm, is the soil transpiration, and 41%, about 3449 mm, is the vegetation transpiration after plants' absorption, which reduce the daily maximum value of air temperature no less than 3.87 °C (Shang et al., 2016). It's proved that only 2% energy from plants' absorption is dissipated by crown, and the rest by transpiration (Shang et al., 2016). Based on above researches, we can calculate that about 82.5% heat is transpired by heat-storage and transpiration of trees and soils.

4. Conclusions

According to the contrastive study on different underlying surfaces by simulating multiple thermal environments with the software of Fluent, some conclusions can be drawn as follows:
(1) The heating effect of the terrain is strong. The air temperature raises 1.9 °C at 12:00 and 0.6 °C at 14:00.

(2) The heating effect of the bare land leads to a decline. The surface and air temperature of the square reduce by 0.5 °C and 0.3 °C, respectively. The surface and air temperature of the hard pavement reduce by 1.02 °C and 0.13 °C, respectively. The North Region's cliff surface temperature and the square surface temperature are both higher than that of the South Region. The North Region's air temperature reduces by 1.6°C.
(3) The effect of trees reduces the surface and air temperature in the shadow area. Forest belts take into the high temperature in the southern square, while it cools down the temperature in the northern square. Water has an obvious characteristic to cool down the temperature. The nearer the place is, the cooler the temperature is.
(4) Compared with the scenario B, the surface temperatures of trees (shadow and inspiration) in the southern square and the northern square both decrease more than 2.5 °C before 12:00, while the air temperature at 12:00 and 16:00 both reduce by 0.17°C and 0.15 °C, respectively. Compared with the scenario C, the surface temperature of trees (shadow and inspiration) between 12:00 and 16:00 declines obviously, and mean values of the air temperature at 12:00 and 16:00 reduce 0.4 °C and 0.42 °C, respectively. Vegetation in Mogao Grottoes cools down the temperature. About 82.5% heat declines for its transpiration.

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