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Numerical Simulation of the Micro Environment in the Han Yang Mausoleum Museum

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ABSTRACT

As a first underground museum in the world, whole sealed glass system is adopted in the Han Yang Mausoleum Museum to protect relics from the destruction by microbe and pollution in the atmosphere and to provide visitors a wonderful environment for enjoying the fantastic artwork closely from different angles. This study shows that, this method cannot completely stop relics from the destruction. The main reason is that, in the museum, the microbe growth and pollution spread are fairly significant to affect the protection of relics. This study numerically simulates the micro environment in the museum, including air movement, temperature and relative humidity by using the CFD software Fluent. The major findings are summaried as the followes: there are four air cyclones; temperature is getting lower from one side to another; and relative humidity profile is reversed, especially at the surface. This numerical result provides useful information for the protection of relics.

***Keywords**:* Han Yang Mausoleum; Museum; CFD modeling; Relative humidity; Fluent.

INTRODUCTION

The Han Yang Mausoleum Museum (HYMM) is the first underground museum with high technology in the world (Murakami *et al*., 2001; Zhang *et al*., 2008). Based on the principle of minimum changes, relics are on their original positions and no ventilation system is utilized. In order to cut off the air exchange, a sealed glass chamber is installed in the HYMM to separate the surrounding environment of the relics and tourists (Christoforou *et al*., 1996; Brimblecombe *et al*., 1999; Weschler, and Shields, 2000; Weschler and Shields, 2003; Zhu *et al*., 2010). The only motive force for the air in the closure is natural convection (Henkes, 1990; Rodrigues *et al*., 2000; Sigey *et al*., 2004), caused by heating system (McQuiston and Parker, 1994; Kim *et al*., 2001; Srebric and Chen, 2002), which is used advanced technological glass.

However, with adopting the above advanced technology, relics are still under destruction by microbe (White and Gass, 1989; Fischer and Dott, 2003) and the condensation of leaked pollutions (White *et al*., 1989; Nazaroff, Salmon *et al*., 1990; Nazaroff and Cass, 1991; Weschler, 2001; Yang *et al*., 2009; Hu *et al*., 2010; Cao *et al*., 2011). Thus the evaluation of environmental parameters in the museum should be conducted (Thomson, 1986; Camuffo, 1998; Nazaroff, Weschler *et al*., 2003). In this study, Fluent is used to numerically simulate (Nazaroff and Cass, 1989) the air movement (Nazaroff, 2004), temperature and relative humidity distribution in the HYMM to evaluate whether the situation in this museum is still appropriated for the preservation of relics.

METHODOLOGIES

In all CFD approaches, the following basic procedures (Wen, 2009) are used:

A. During preprocessing
   a) The geometry (physical bounds) of the problem is defined.
   b) The volume occupied by the fluid is divided into discrete cells (the mesh). The mesh may be uniform or none uniform.
   c) The physical modeling is defined, e.g., the equations of motions + enthalpy + radiation + species conservation
   d) Boundary conditions are defined. These include specifying the fluid behavior and properties at the boundaries of the problem. For transient problems, the initial conditions are also defined.

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B. The simulation is started and the equations are solved iteratively as a steady-state or transient.
C. Finally, a postprocessor is used for the analysis and visualization of the resulting solution.

In this study, Fluent is used as postprocessor. The energy and full buoyancy effect options are on, meanwhile, the standard k-e model and standard wall function (Gu, 2010) are used in the model in Table 1. Steady state, incompressible flow is assumed in this study (Chen *et al*., 2007). Therefore, the governing equations (equations of continuity (1), momentum (2) and energy (3)) of heat transformation for natural convection are shown as followes:

$$\frac{\partial u_j}{\partial x_j} = 0 \tag{1}$$

$$\rho\frac{\partial u_i}{\partial t} + \rho\frac{\partial (u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + g\beta\rho(T - T_c) - \delta_{i3} \tag{2}$$

$$\rho\frac{\partial e}{\partial t} + \rho\frac{\partial (eu_j)}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{u}{Pr}\frac{\partial e}{\partial xj}\right) \tag{3}$$

where g is acceleration due to gravity, ρ is the density, μ is the dynamic viscosit, β is the volume thermal expansivity and T is the temperature

The source term for momentum equation is thermal buoyancy which is $-\rho\beta\delta_{i3}$ in Eq. (2).

In the simulation, one assumption is that the indoor flow is mainly due to buoyant and turbulent because of the sealed glass heating system. In order to obtain the turbulent flow field, the well-known $k-\varepsilon$ turbulence model with buoyancy terms for $k-\varepsilon$ is employed (Panagopoulos *et al*., 2011). The standard values of the model constants C_μ, $C_{\varepsilon1}$, $C_{\varepsilon2}$, σ_k, and σ_ε are $C_\mu = 0.09$, $C_{\varepsilon1} = 1.44$, $C_{\varepsilon2} = 1.92$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$.

Boundary Condition

Because there are no inlet and oulet velocities, the boundary condition setting is fairly simple, and only thermal condition with two scenarios is considered. For the glass heating case, 20°C and 24°C are assumed for the sides of pits and glass, while for the sides heating case, 25°C and 20°C are used for the sides of pits and glass, respectively (Table 2).

Grid Generation by Gambit

As shown in Fig. 1 and Fig. 2, the model includes 8 pits and the display hall is divided into 5 parts: they are

1) Sides of pits in vertical direction
2) Bottom of pits in horizontal direction
3) Large number pieces of glass
4) Two walls
5) Insulations and ceiling

The height of the model is from –2.6 m to 5 m in z direction. The width is from 0 to 54.5 m, and the length is from 0 to 55 m.

Table 1. Model setting in Fluent.

Model Setting	
Gravity	9.81 m/s^2
Energy	On
Model	Standard k-epsilon
Near wall treatment	Standard wall function
Option	Full buoyancy effect

Table 2. Boundary condition in the model.

Name	Type	Thermal condition
Walls	Wall	None
Sides of pits	Wall	25°C/20°C
Bottoms	Wall	20°C
Glass	Wall	20°C/24°C
Ceiling	Wall	None

RESULTS

As shown in Table 1, sides of pits and glass are treated as wall types with fixed temperature. So far, the whole sealed glass system heats the glass to 24°C constantly in order to keep the temperature of the hall around 22°C which is required (Brimblecombe, 1990; Pavlogeorgatos, 2003) for relic preservation. The temperature of sides of pits is 20°C in the museumum.

Calculation Residuals

As shown in Fig. 3, except k and epsilon residuals, others are stable. The reason for the situation of k-epsilon is probably due to the fact that the natural convection is essentially unstable (Choi *et al*., 2004).

Air Movement in the Hall

In this case, the air movement is mainly natural convection caused both by gravity and temperature gradients. Although air velocity is extremely small from 1.11×10^{-3} m/s to 8.77×10^{-2} m/s as shown in Fig. 4, there are four gas cyclones in the 3 m (altitude) plane which is at 6 m hight from the bottom. It shows that the horizontal air movement caused by the temperature difference between pits and glass is more regular than the vertical air movement based on gravity. This phenomenon will improve thermal and humidity exchange; on the other hand, the material exchange brought by gas cyclones will lead pollutant diffusion to destroy relics on the bottom in the display hall. Fig. 4 also indicates that these 8 pits can be divided into 4 parts: i.e., pit 21, 20, 19, pit 18, 17, pit 16, 15, and pit 14 since these cyclones will affect the surrounding condition.

Temperature Distribution

To see the detail distribution, we narrow the range from 21.2°C to 22.2°C. As shown in Fig. 5, temperature in pit 21 is around 21°C to 22°C which fulfills the preservation request, but there is a large gradient and a temperature distribution layer. In order to eliminate those dissociative points besides heating glass and cold earth, and to get detail data for pit 21 to pit 16, more detailed information is shown in Fig. 7.

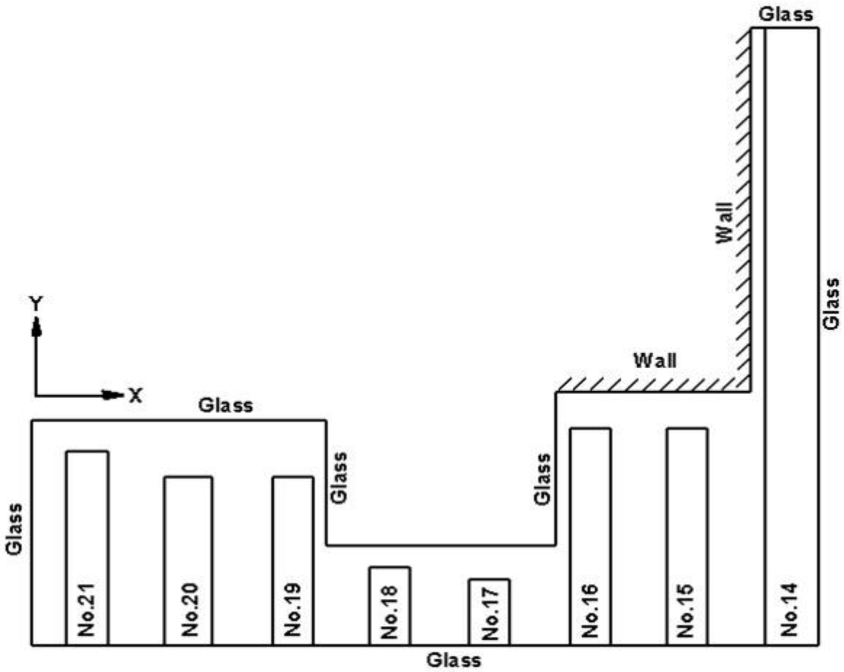

Fig. 1. Draft of model for display hall of Han Yang Mausoleum museum.

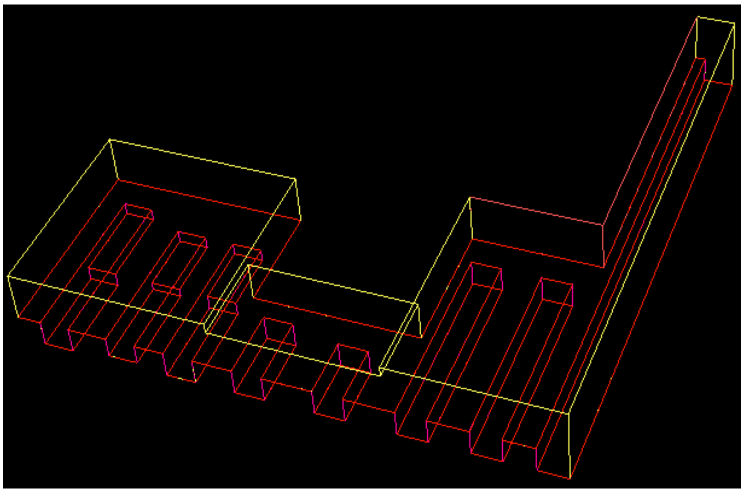

Fig. 2. Grid generated by Gambit in five parts.

As shown in Figs. 6 and 7, there is a regular temperature increase from low place to high place, a gradient, and a temperature distribution layer (Zhao, 2005), which suggest that the temperature distribution cannot reach the requirement for relics' preservation and improvement is needed.

Based on all the faces, whole situation temperature is getting lower from pit 21 to pit 14, which indicates one side of the hall is colder than the other side especially at the lower position.

Relative Humidity Distribution

To simulate the evaporation rate, we set the boundary condition and for the bottoms of pits and sides of pits with H_2O mass fraction to be 0.015. As shown in Fig. 9, there is a gradient and the RH values are getting smaller from low to high position which is the opposite compared to the temperature distribution.

In this display hall, the lowest RH is around 88% while the highest one is around 93.5%, therefore the overall difference between highest and lowest RH is around 7.5%. The RH values are getting lower from pit 21 to pit 14, which indicate RH is higher in one side of this hall than other side. The change in low place is bigger than in high place. Near the floor (z = –2.6 m), the lowest RH is 90.5% in pit 21 while the highest RH is 93.5% in pit 19, suggesting that the difference of RH is 3.5%. Results in Fig. 9 further demonstrate the existence of an obvious gradient and a RH distribution layer.

The diurnal variation of the relative humidity is mearsured in pit 16. It is between 88% to 90%. Compared with the measured data, the modeling data for RH between 88% to 93.5% is considerably reliable.

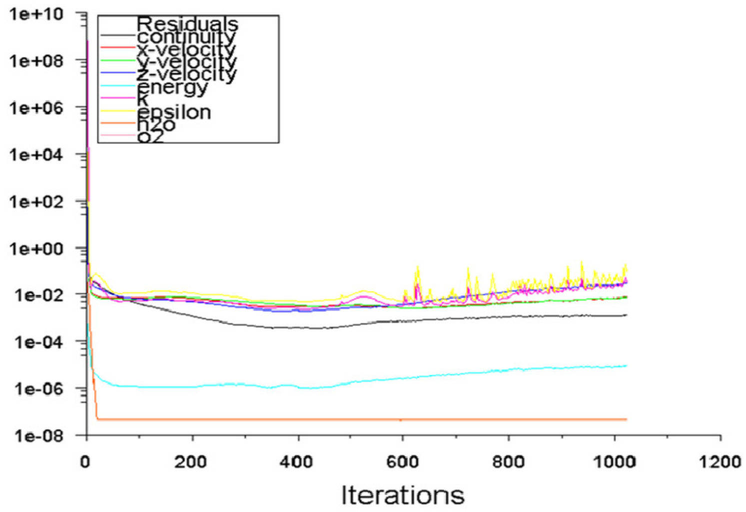

Fig. 3. Residuals of all the indexes in calculation.

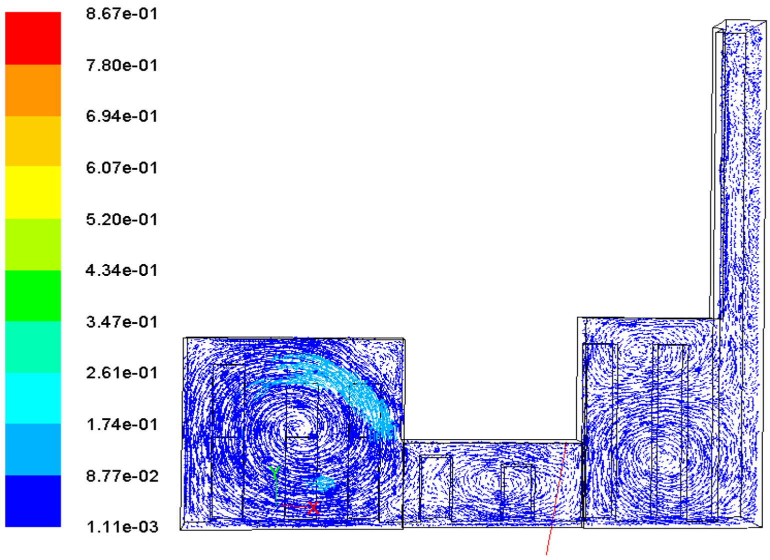

Fig. 4. Air movement in the plane of z = 3 m.

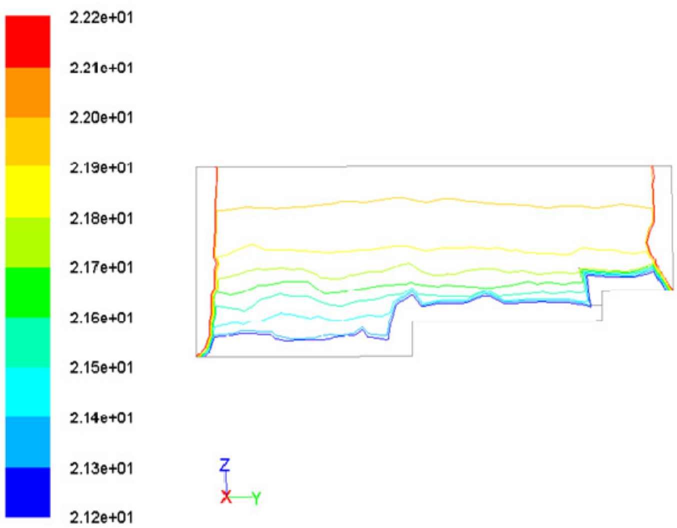

Fig. 5. Temperature distribution in plane x = 3.9 m for pit 21.

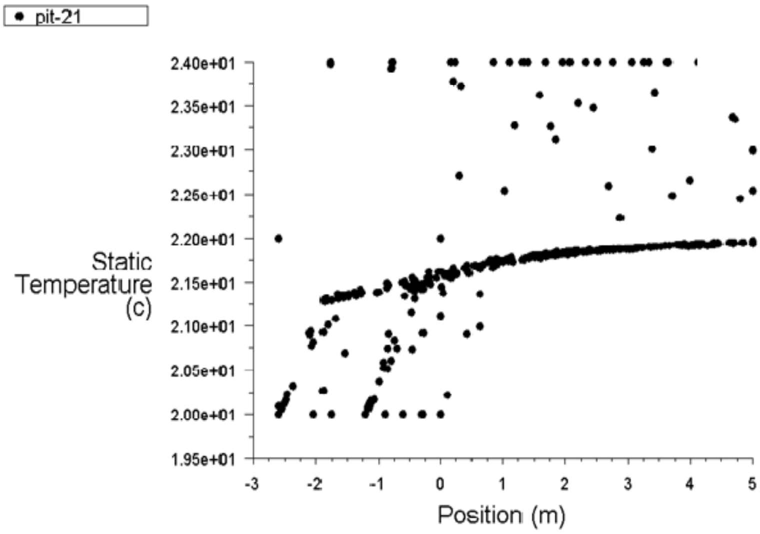

Fig. 6. Data about relationship between temperature and z direction position in plane x = 3.9 m for pit 21. Horizontal axis is the position in z direction which is vertical direction in model.

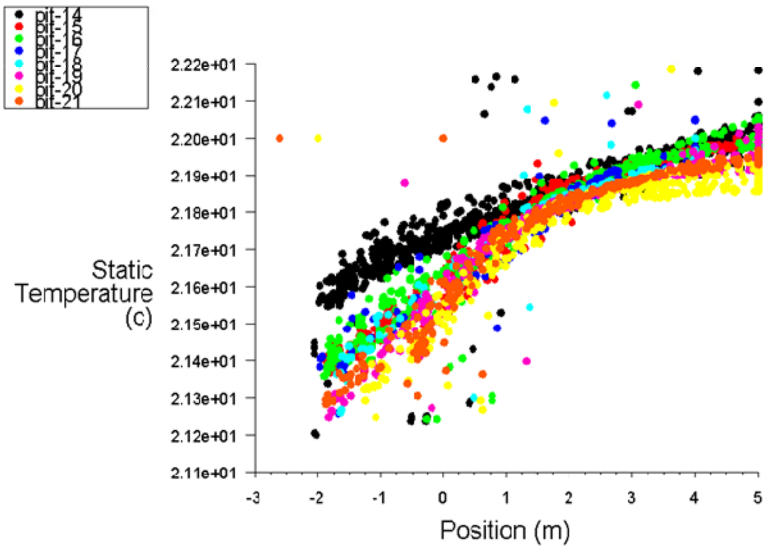

Fig. 7. Relationships between temperature and position for all 8 pits in 8 chosen planes in the range of 21.2°C to 22.2°C.

Estimation of a Suggested Case for Heating System

As the simulation shown in Fig. 7, improvement is needed because of the large gradient and the layer for temperature and RH distributions. Some preveous studies suggested that heating the sides of pits instead of heating the glass could solve the problems (Luo and Gu, 2007). To result the request of preservation temperature, temperature of sides of pits is settled 25°C and temperature of glass is settled 20°C due to air conditioning system outside the display hall.

Simulation Result of the Given Suggested Scenario

Since relative humidity (RH) is the most significant factor among temperature, RH and air movement for relics preservation, Figs. 11 and 12 show the RH result of the suggestion case. As shown in Fig. 11, apparently RH is higher in the –x direction than that in the +x direction.

Comparison between Suggested Case and Current Case

We note that, RH is getting lower from pit 21 to pit 15 at all heights (situation at pit 14 is complex because of its huge scale). As shown in Figs. 7, 10, 12 and 13, although there is a large gradient in actual case while no gradient layer is in suggested case, differences of temperature and RH between pits still exist. This study suggests that future improvement of the suggested case is still necessary to reduce the difference of relative humidity between pits.

DISCUSSION

Role of Relative Humidity

At the present, the display hall of Han Yang Mausoleum is with high relative humidity 97% measured on June 2010. On the one hand, high RH will lead further destruction of relic since it provideds a favorable condition for the

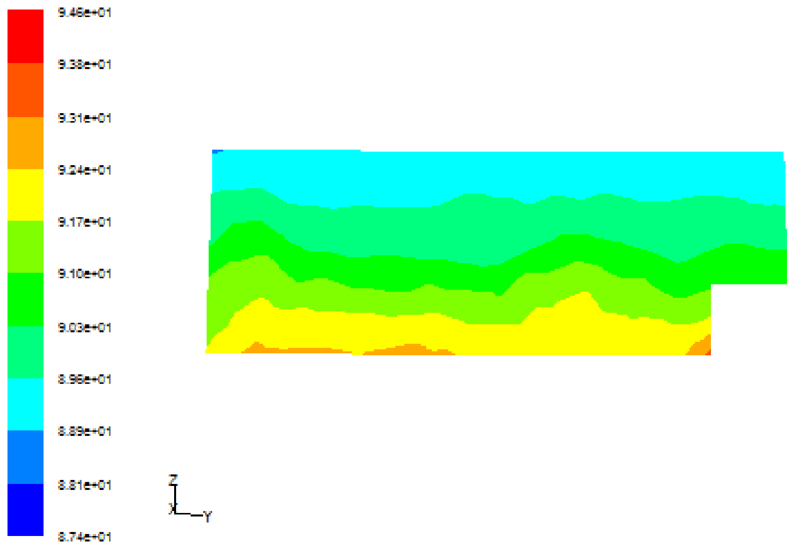

Fig. 8. RH distribution for pit 16.

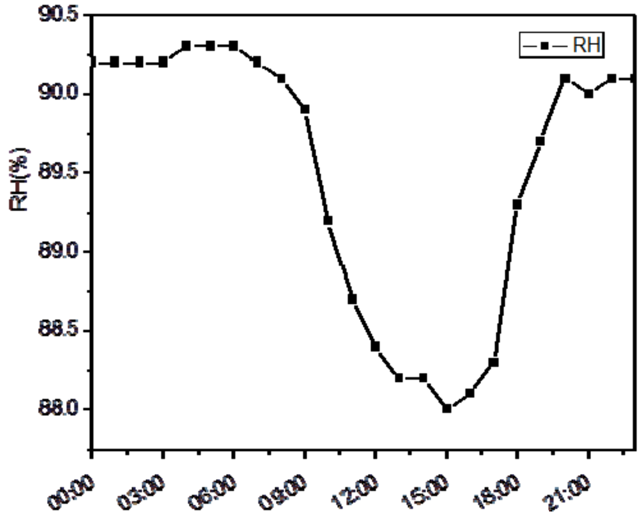

Fig. 9. the measurement of Relative humidity in the museum based on the diurnal diviation.

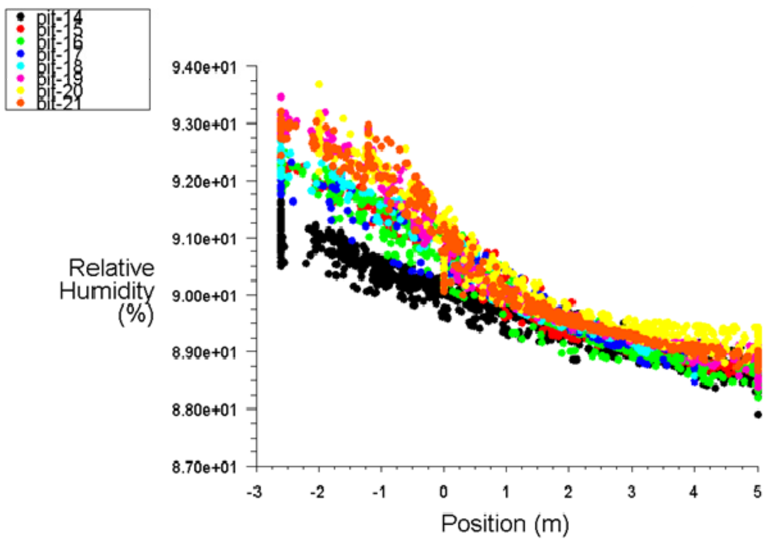

Fig. 10. Relationships between RH and position in z direction for all 8 pits in 8 chosen planes.

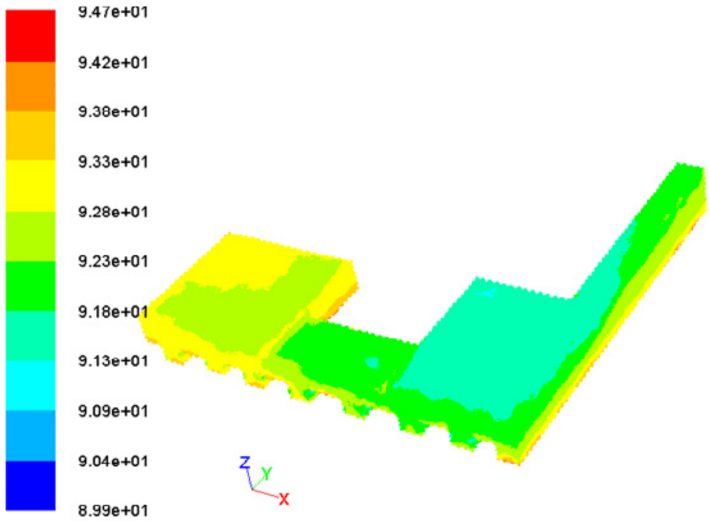

Fig. 11. Overall RH distribution in the suggestion program.

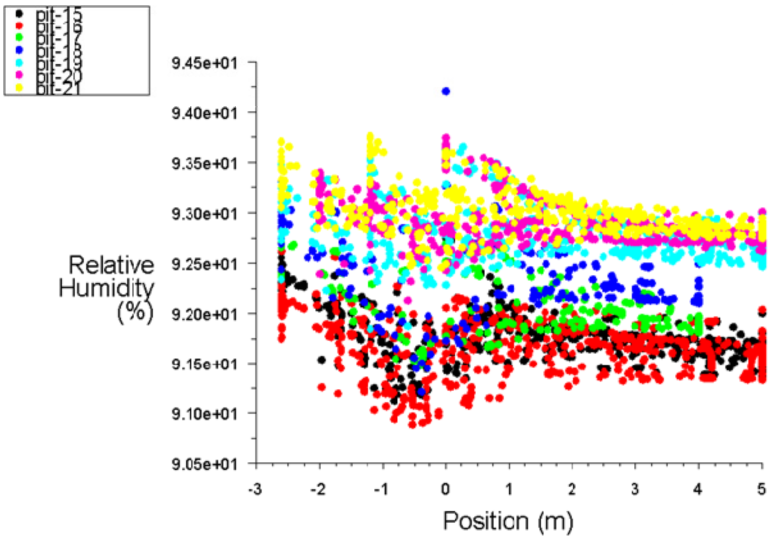

Fig. 12. RH simulation for suggested case. This is the relationship between RH and position in z direction for all 8 pits.

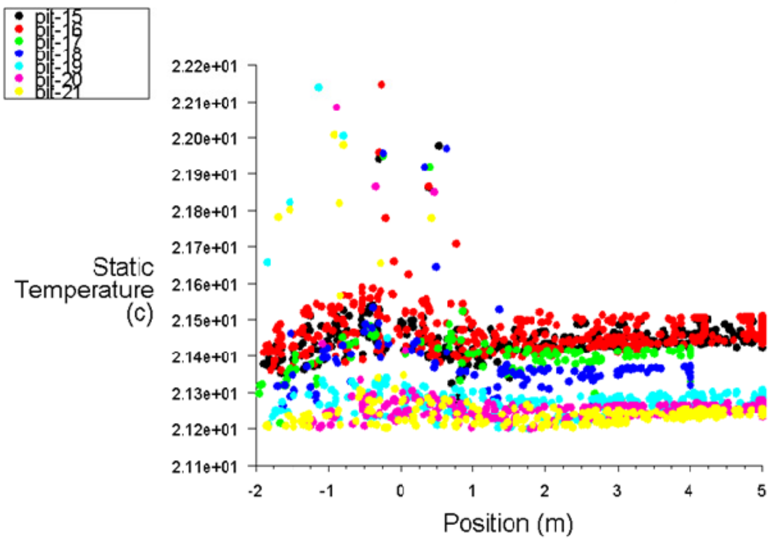

Fig. 13. Temperature simulation for suggested case.

coagulation and sedimentation of pollutant gas (such as SO_2 and generate crystalloid salt) on the face of relic. On other hands, the high RH restrained the growth of microbe since the most RH values are between 70%–80%. Therefore, it needs further theoretical and practical studies and researches to decide the best relative humidity for the relic preservation.

Limitation for the Evaporation of Earth

It will be a costly experiment to measure separately all the evaporation rates which are related with underground water for the surrounding surfaces in this large display hall. For simplicity reason, we set the value of H_2O mass fraction is 0.015 for earth instead of evaporation rate in the simulation.

Ignorance of Air Leakage

Since it is not clear about the display hall leakage situation which includes the exactly location and nearly speed of leakage, the model in this study just ignore the leakage. Although the leakage rate is 0.04/h (Li *et al*., 2010), which is extremely small, it still has some effects on the simulation of temperature and relative humidity. With this leakage, the exchange in and out the display hall exists and the environment outside display hall must be considered. The outside display hall temperature and RH, which change largely in the whole year, have influence the simulation in different ways. While the leakage detection is still on our further research schedule, the current simulation which has ignored the air leakage gives some uncertainties. Without knowing the exact leakage situation, the relationship between temperature and RH in and out the display hall cannot be included in the model, which largely limit the application of this model.

CONCLUSION

As the first modern underground museum, the display hall of Han Yang Mausoleum Museum is with special style. The relic preservation method is a new attempt. With discovering problems in the relic zone, this study simulated the micro environment for several parameters which includes temperature, air movement and relative humidity and provide useful information for the furture protection, and some conclusions are goven as the followes:

1) Under the actual heating system (whole sealed glass system), four obvious gas cyclones are found in display hall. However cyclones only exist in high-level, limiting the the thermal exchange in low-level. Therefore increase in the cycling air in the lower level is adversed for the relic preservation in display hall.
2) Large gradient and layer of temperature and RH distribution exist in every pits, which are not good for relic preservation. Temperature is getting lower from pit 14 to pit 21 while RH is getting lower from pit 21 to pit 14 among 8 included pits. The differences are even larger in low height near the ground. These situations lead to unstable and harmful environment for the relic preservation.
3) The RH and temperature in some suggested case are simulated. Although the large gradient layer disappeared, some differences between pits still exists. As a result, this suggested case should be improved to reduce the difference between pits.

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