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Numerical Simulation ofVentilated Archeological Tomb of Horemheb, Valley of The Kings, Luxor

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***Abstract**: The present research targets to study the effect of mechanical ventilation systems on airflow patterns, in addition to relative humidity distribution and temperature inside the tomb of Horemheb (KV57) and the thermal comfort prediction through this work was based on the PMV (Predicted Mean Vote) model and the PPD (Percentage Predicted Dissatisfied) model, the PMV and PPD were estimated using Fanger's model. The study was executed using computational fluid dynamics (CFD) simulation using a commercial CFD code. The CFD modelling techniques solved the equations of energy, momentum, continuity and species transport as well as k-epsilon model equations for turbulence closure. The SIMPLEC algorithm was utilized for the pressure-velocity coupling and a second order upwind scheme was use for discretization of the governing equations. All mesh sizes that used in the present work went above 8,000,000 mesh volumes which allowed meaningful and better predictions of the flow regimes.*
***Keywords**: CFD, Thermal Comfort, KV, PMV, PPD*

I. Introduction

The tombs of the kings in Valley of the Kings, Luxor, are considered to be one of the tourism industry's bases in Egypt due to their uniqueness all over the world. Hence, they should be preserved from the different factors that might harm their wall paintings. One of these factors is the excessive relative humidity as it increases the bacteria and fungus activity inside the tomb in addition to its effect on the mechanical and physical properties of materials. Throughout the investigations which were made, the number of visitors, the outside air conditions, and the airside system design impact on the tomb's airflow characteristics were subject to study in order to reach the optimum ventilation design besides the conditions suitable for work. The optimum airside system design is supposed to allow the air pass all the enclosure areas before being extracted. Furthermore, limitation should be made for the simultaneous number of visitors for the tomb KV57 so as to restrict and control the relative humidity inside the tomb. The present work was made using of packaged Computational Fluid Dynamics (CFD), following other earlier similar work of AbdelAziz et al (2005) [1], Hussien et al (2006) [2] and Osama et al (2008) [3].

II. Tomb Kv57 Configuration

Horemheb tomb, KV 57 is composed of two parallel axes, the first axis start with entrance and corridors and after then we find well chamber and then pillared chamber including second axis, which leads to the burial chamber. The site of tomb is located at 25.44 North Latitude and 32.36 East Longitude. The tomb is 173.24 m above sea level. The maximum height is 5.36 m; minimum width is 0.66 m, while the maximum width is 8.94 m. The tomb total length is 127.88 m. The floor area is measured to be 472.61m², while the total volume is 1328.17 m³. These engineering data files are already on the Web site created by TMP [6].

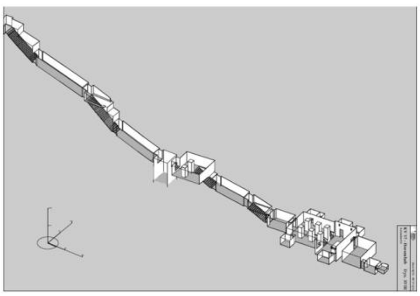
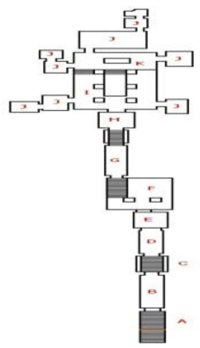


Figure 1: Tomb of Horemheb Configuration

A - Entrance stair
B - First corridor
C - Second corridor
D - Third corridor
E - Well chamber with well shaft
F - First pillared hall
G - Fourth corridor
H – Antechamber
I - second pillared hall
J - Store rooms
K - Burial chamber



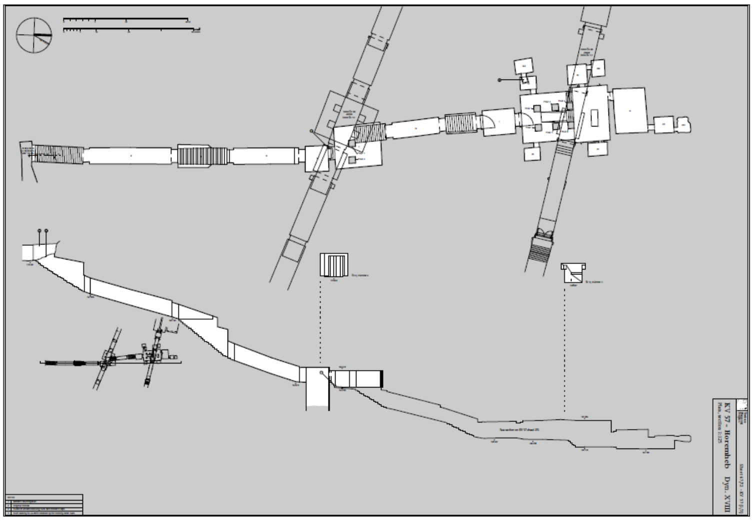


Figure 2: Schematics of Tomb Axes

III. Numerical Investigations

3.1. Governing Equations

The different governing partial differential equations are typically in the general form, (Khalil; 2000 and Kameel; 2002) [4, 5] in 3D configurations under steady conditions, as:

$$\frac{\delta}{\delta x}\rho U\Phi+\frac{\delta}{\delta x}\rho V\Phi+\frac{\delta}{\delta x}\rho W\Phi=\frac{\delta}{\delta x}\left(\Gamma_{\Phi,eff}\frac{\delta\Phi}{\delta x}\right)+\frac{\delta}{\delta y}\left(\Gamma_{\Phi,eff}\frac{\delta\Phi}{\delta y}\right)+\frac{\delta}{\delta z}\left(\Gamma_{\Phi,eff}\frac{\delta\Phi}{\delta z}\right)+S_{\Phi}$$

Where:

ρ = Air density, Kg/m^3.
S_Φ = Source term of Φ.
Φ = Dependent variable.
U, V, W = Velocity vectors.
$\Gamma_{\Phi,eff}$ = Effective diffusion coefficient.

The diffusion coefficients and source terms for the differential equations can be found in reference by Khalil(2008).

3.1. Boundary conditions and assumption

The following more important boundary conditions assumptions were made in the present investigations.

1. The inlet air condition are taken as the average day max of 40^{o}C (313K) and 30% relative humidity (humidity ratio = 0.0138), respecting to August conditions, the outside air conditions all over the year can be found in Egyptian code[7], when air is admitted freely to the tomb, the turbulence intensity could be assumed to be 5% and the length scale is assumedto be 1m.
2. The air outlets are set as outflow conditions where the specification of the flow rate weighing can differ from one outlet to the other in order to allow more flexibility.
3. The walls are deep inside the earth, they are treated as a block kept at constant temperature, which is the wet bulb temperature or dew point temperature for outside air condition, representing to August conditions,

using the psychrometric chart can find that the outside air wet bulb temperature 25^{o}C, the walls assumed have zero species, zero water vapour, and zero diffusion flux.

4. The visitors' bodies is treated as a wall at a constant temperature (isothermal wall), where the skin temperature is a function of metabolic rate, the visitors has been assumed the metabolic rate is 116 W/m2 (2 Met), this is equivalent to 32.5ºC skin temperature, and the body is assumed to have zero diffusion flux.
5. The visitors' faces are considered as isothermal walls kept at the human skin temperature of 32.5ºC as well. Also it is assumed that there is a specified species mass fraction of 0.0411 kgw/kgd.a in order to take into account the sweat effect in moisture gain to the tomb airflow.

3.3. Computational Results

Over 8 million computational cells were used to map the tomb total volume 1328.17 m³, more than 1500 iterations were necessary to achieve the convergence criteria. The application of CFD simulation in the indoor environment is based on conservation equations of energy, mass and momentum of incompressible air. The turbulence model used in the numerical model is the widely used standard k-ε model. Some researchers [8] indicated that the k-ε model of turbulence [9] was the most appropriate model for practical building airflow applications

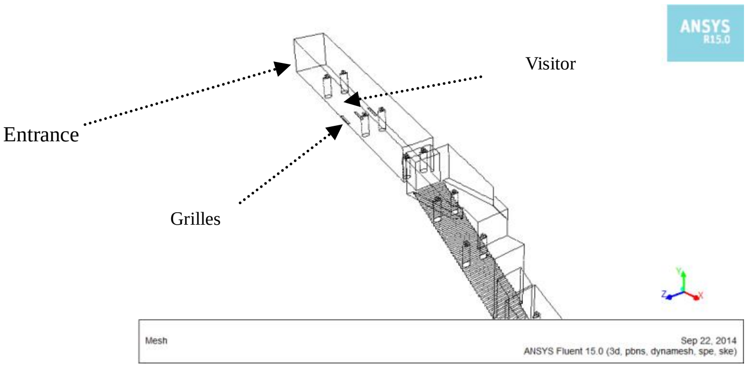


Figure 3: Computational Cell Representing Ventilation Grilles

IV. Simulation And Discussions

In purpose of the appropriate ventilation system designs, simulation of actual air flow patterns and heat transfer behavior was carried out with the above computational scheme. Air outlets are located on the raised floor in order to keep the archaeological scheme unaltered. The air outlets may be located either near the side walls or at the floor center allowing a diversity of airside system designs.

The grid independency check achieved through comparisons of the same case for different grid sizes of 2281004, 4589565, 6156217 and 8117581. The comparison is made through line plots at the location above the sarcophagus. The burial zone is of prime importance due to visitors grouping around the sarcophagus. The predictions of the temperature distribution for different mesh size shown in figure 4 below.

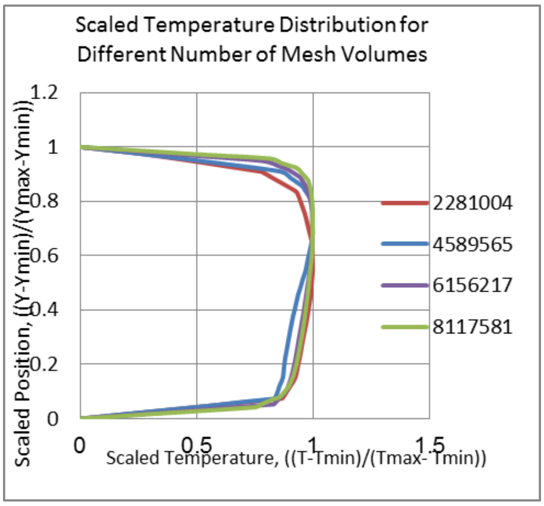


Figure 4: Comparisons betweenDifferent Mesh Sizes for Temperature Distribution

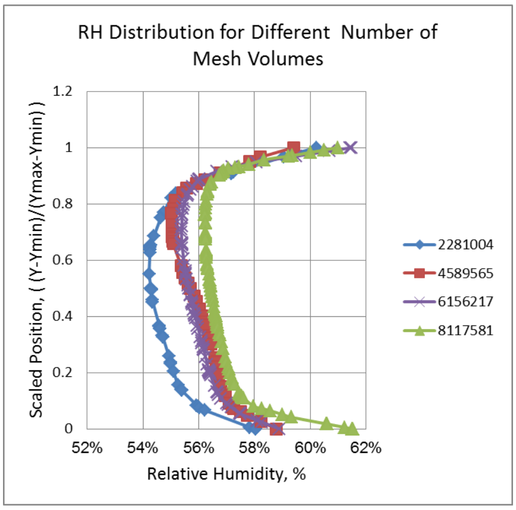


Figure 5: Comparisons betweenDifferent Mesh Sizes for RH%Distribution

The tomb model design incorporated 52 grilles 1.0×0.15 m for air mechanical extraction to provide minimum air velocity near walls in order to prevent erosion of the walls, figures 6, 7 show the velocity higher that 0.12 m/s are only found in the entry of the tomb up till section F (well chamber), after that the velocity are low as required to prevent erosion of the paintings.

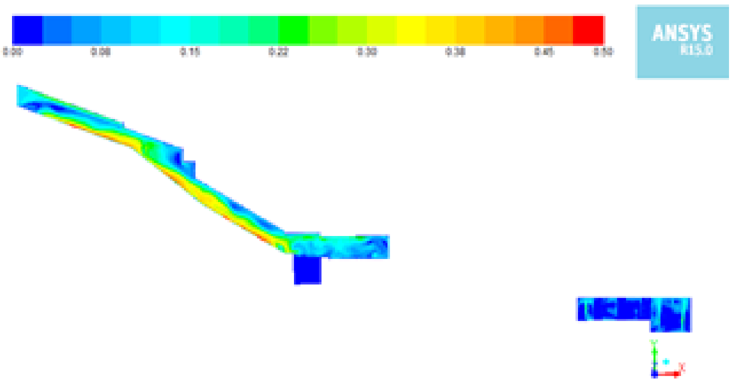


Figure 6: Velocity Magnitude Contours, m/s, for a Mid-plane along the Tomb Axis-1

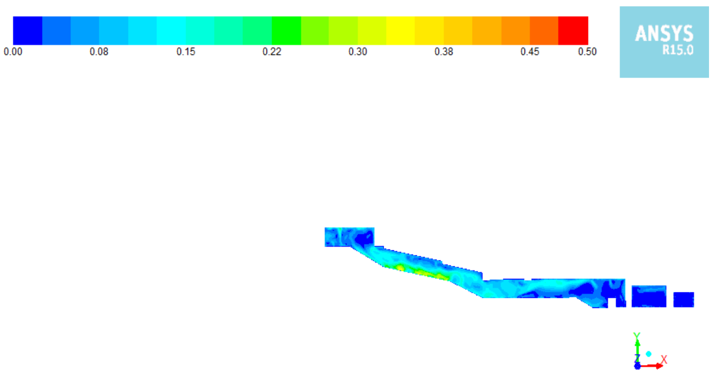


Figure 7: Velocity Magnitude Contours, m/s, for a Mid-plane along the Tomb Axis-2

From previous figures 6,7 velocity higher that 0.12 m/s are only found in the entry of the tomb up till section F (well chamber), after that the velocity are low as required to prevent erosion of the paintings.

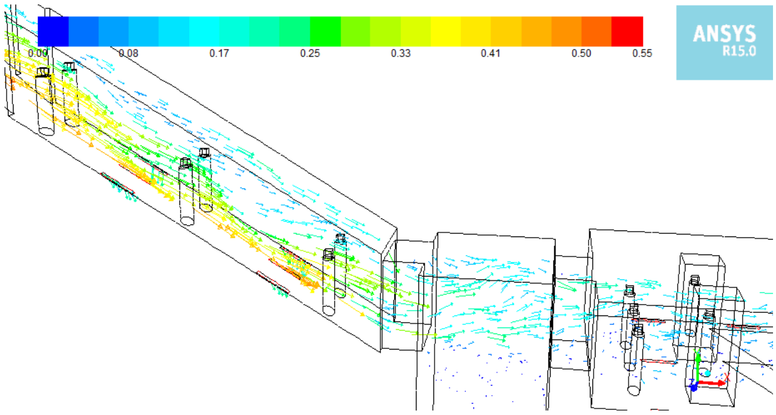


Figure 8: Velocity Vectors, m/s, along mid planeAxis-1 in Section D and Well Chamber

Vector plot in figure 8 indicate the mechanical extraction provides a smother flow pattern with less recirculation zones inside the tomb KV57.The figures below show that temperature decrease from 313 to 305K (August outside air condition) inside the tomb KV57, 52 grilles take 8% of the tomb as shown in figure below.

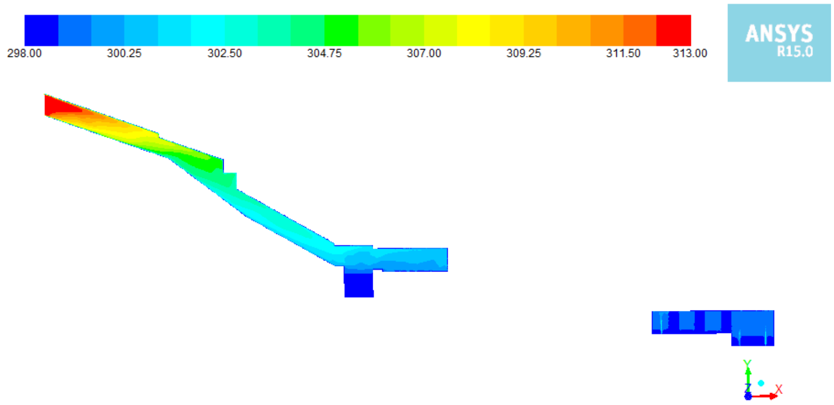


Figure 9: Air Temperature Contours, ^{o} K, for Mid-plane along the Tomb Axis-1 at August outsideAir Conditions

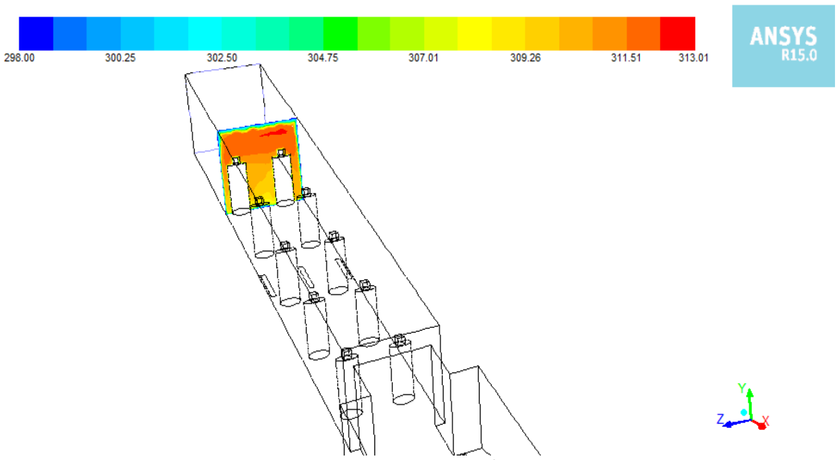


Figure10: Air Temperature Distribution, ^{o}K,for a Planeat x = 3.5m

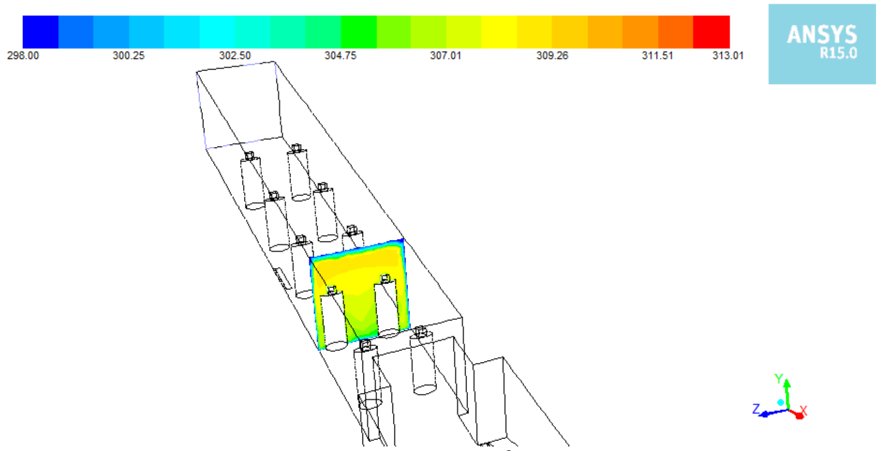


Figure 11: Air temperature distribution, ^{o} K, for aPlane at x = 10m

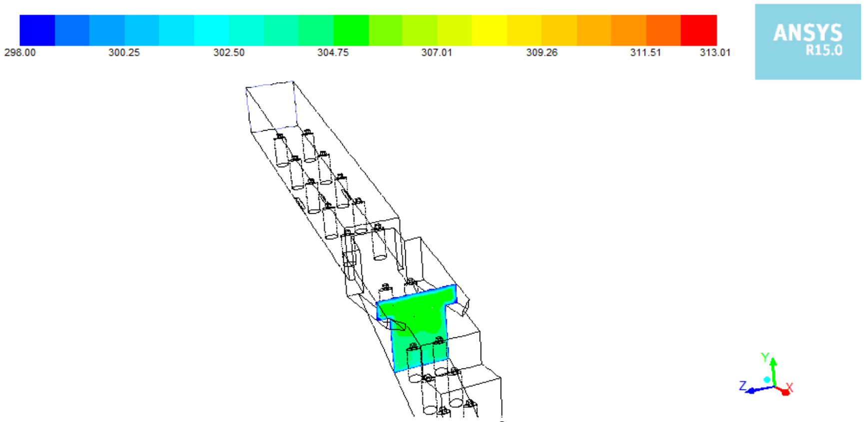


Figure 12: Air Temperature Distribution, ^{o} K, for a Plane at x = 18m

From relative humidity predictions find the max RH at the wall is 70% and the RH varies from 63% to 69% in burial chamber that shown in figure 12 for RH in mid-plan axis 2, The comfort zone is based on the PMV values between -0.5 and +0.5 [10,11,12] and PPD value is 25%.

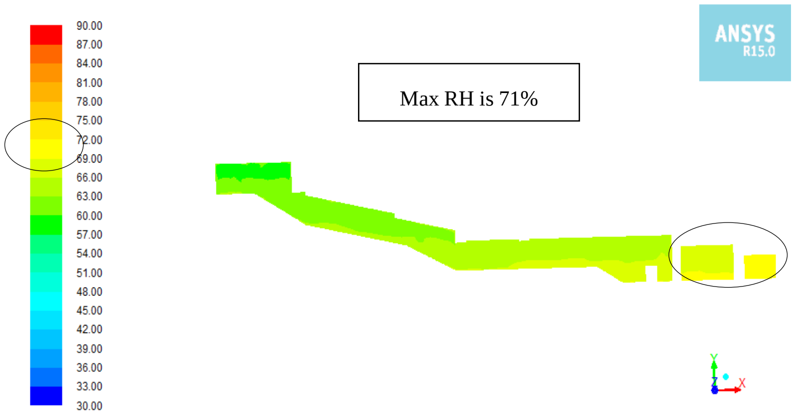


Figure 13: Predicted RH %,Contours Axis-2 for 42 Visitors.

The number of persons does not affect the relative humidity in the tomb to a great extent, a comparison between different number of occupancies shows that the relative humidity decreased with the decrease of the number of people inside the tomb, however this decrease is very small as the max RH decreased from 75% (85visitors) to 73% (65visitors) then further to 71% (42visitors), the relative humidity only varied by 4%.

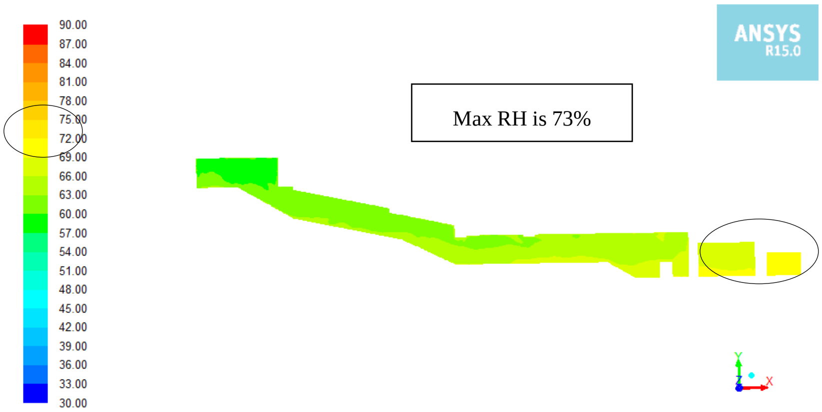


Figure 14: Predicted RH % Contours Axis-2 for 65 Visitors.

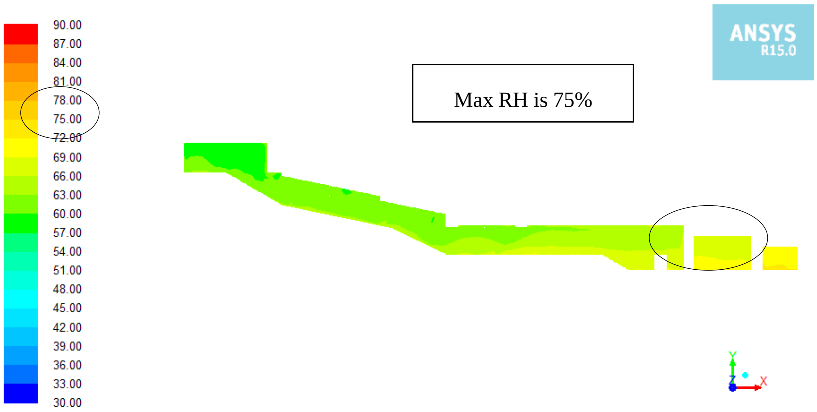


Figure 15: Predicted RH%Contours Axis-2 for 85 Visitors.

The effect of outside air conditions from simulation indicates that RH increases at all time ofthe year with exception of June, July, August, September and October so opening the tomb at these months is save from excessive relative humidity that cause the problem with mold, corrosion, decay and other moisture related deterioration. The maximum calculated relative humidity was as high as 70% in June,73% in September,78% in November and 82% in December; that makes excessive visiting in December is risky for the artifacts.

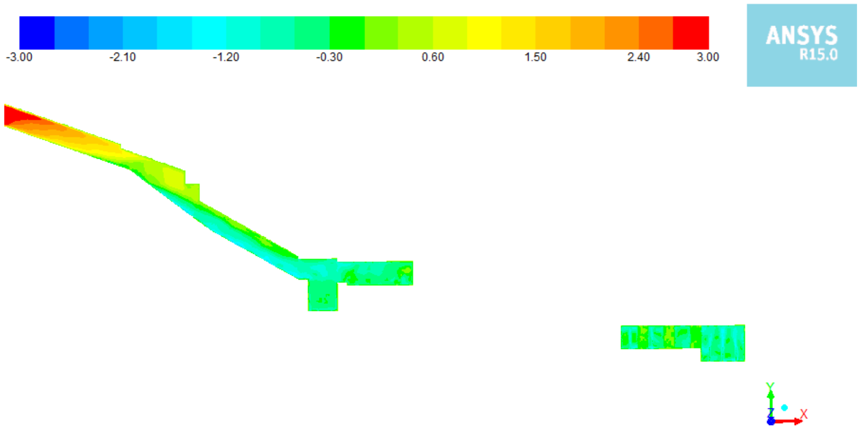


Figure 16: PMV Contours for a Mid-plane along the Tomb Axis-1, AugustoutsideConditions

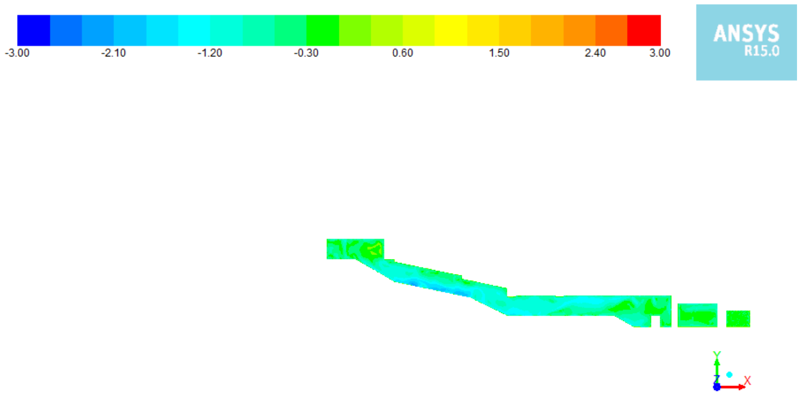


Figure 17: PMV Contours for a Mid-plane along the Tomb Axis-2, August outside Conditions

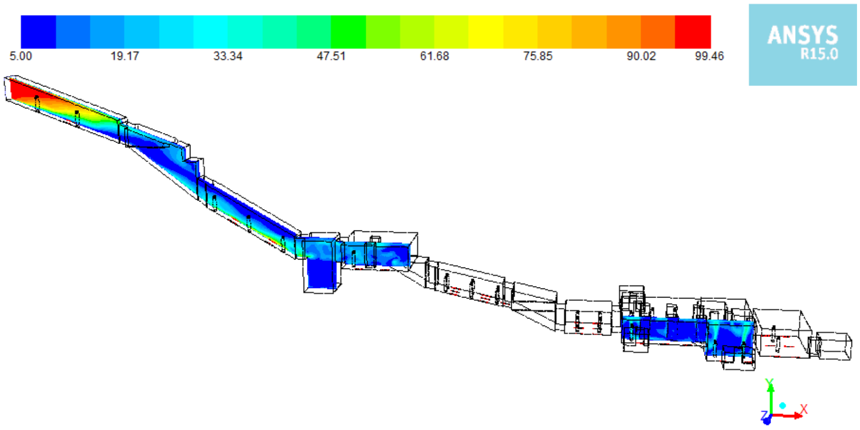


Figure 18: PPD contours for a Mid-plane along the Tomb Axis-2, August outside Conditions

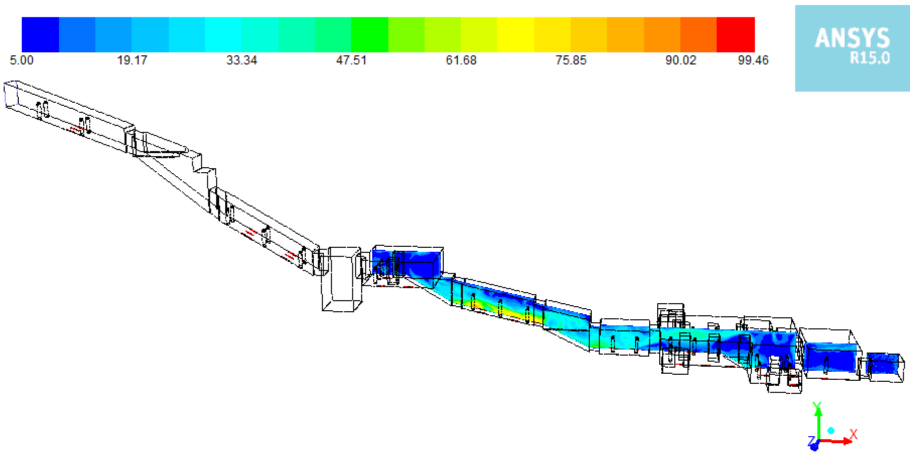


Figure 19: PPD Contours for a Mid-plane along the Tomb Axis-2, August outside Conditions.

V. Conclusions

The present work presented before was performed to enhance the understanding of flow regimes and thermal patterns and ventilation system characteristics in the archaeological tomb KV57.From results one can find that the relative humidity in the tomb is not affected greatly by the number of persons inside the tomb, the performed results show that the relative humidity inside the tomb is highly affected by the outdoor air conditions as the max relative humidity in the months June, July, August and September is 75%, for the rest of the year at all times,the year relative humidity increases to about 75% so these months it is not recommended to open the tomb for visitors due to the higher values of relative humidity, and the air velocity inside the tomb should not exceed 0.12 m/s in order not to create any undesired drafts. It is therefore recommended that the velocities in the vicinity of the floor mounted extracting grilles can be accepted to be higher than 0.12 m/s, while the values of the velocities in the rest of the domain are generally less than 0.12 m/s , particularly in the wall vicinity. Velocities higher than 0.12 m/s are only found at the entry of the tomb up till well chamber, after that the velocities areof lower values to prevent erosion of the wall paintings.

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