Building Simulation 2009

Eleventh International IBPSA Conference
Glasgow, Scotland
July 27-30, 2009

CFD APPLICATIONS FOR THE PRESERVATION OF THE TOMBS OF THE VALLEY OF KINGS, LUXOR

Prof.Dr.Essam E Khalil, Fellow ASME, Fellow AIAA, Member ASHRAE
Professor of Mechanical Engineering
Cairo University, Cairo-Egypt

ABSTRACT

The tombs of the Pharonic kings in "valley of the kings", Thebes, Egypt are famous for their unique wall paintings and structure. KV62, King Tutankhamen tomb, is the most famous because of the treasures it held intact for over three thousand years. The tombs of Kings Ramses VII, known as KV1, Ramses IV, (KV2) and Siti II (KV15) were also investigated in the present work. The present work pursues a research plan to design and utilize a CFD model to numerically model the flow pattern, heat transfer and humidity in the tombs. A commercial CFD package was used to simulate the indoor air conditions, air flow velocities, temperatures and relative humidity patterns in the tombs. Still all shown predictions clearly indicated the usefulness of raised-floor extracts that do not disturb the archeological value of the tombs and do not install any artificial materials inside the tombs.

INTRODUCTION

To design an optimum HVAC airside system that provides comfort and air quality in the air-conditioned spaces with efficient energy consumption is a great challenge. Air conditioning can be defined as the conditioning of the air to maintain specific conditions of temperature, humidity, and dust level inside an enclosed space. The levels of the air conditions to be maintained are dictated by the local environment, type and number of visitors and required climate and the required visitors comfort and property reservation. The comfort air conditioning is defined as "the process of treating air to control simultaneously its temperature, humidity, cleanliness, and distribution to meet the comfort requirements of the occupants of the conditioned space", ASHRAE(2005).For the present work, following similar work of AbdelAziz (2005)and Khalil(2006), a numerical study is carried out to define the optimum airside design of the tombs air ventilation and conditioning systems, which provides the optimum comfort and healthy conditions with optimum energy utilization. The present work made use of packaged Computational Fluid Dynamics (CFD) programs under steady state conditions in the tombs under various visitors' scenarios. Basically, air flow regimes are investigated here for the tomb passage of King Ramsis VII, Ramsis IV, Siti II and Bay including different visitors (obstacles) alternative positioning and numbers to draw a guide for he accepted number of visitors at one time to limit excessive humidity ratios. The primary objective of the present work is to assess the airflow characteristics, thermal pattern and moisture content in these different ventilated tombs. The paper ends with a brief discussion and conclusions.

Problem Formulation

The geometrical configuration of the tombs discussed here is that of simple single axis passage, similar to a blind-ended corridor. The tombs are cut into the base of a hill on the northwest side of the main wadi of the Valley of the Kings. The tombs, generally consist of three gently sloping corridors zones, with the sarcophagus located near the deadened corridor .The airflow distribution in a ventilated tomb at its final steady pattern is a result of different interactions such as, the air grilles distributions, artifacts and objects distributions, thermal effects, occupancy movements, etc. The free air supply and mechanically extracted ducted air play an important role in the main flow pattern and the formation of the main air distribution regimes. The visitors inside the tomb interrupt the airflow pattern by creating recirculation zones, deflecting the airflow pattern and acting as heat and moisture sources. This paper follows earlier publications that were limited to the flow patterns in the tomb of Ramses VII, (AbdelAziz, 2005) and (Khalil, 2006). The present work is an extension that covers some more complicated and longer tombs and is the aim is to demonstrate the need for mechanical ventilation for longer tombs (more length inside the mountains).

METHOD DESCRIPTION

Model Equations

The program solves the differential equations governing the transport of mass, three momentum components, energy, relative humidity, and the mean age of air in 3D configurations under steady conditions. The different governing partial differential equations are typically expressed in a general form, Khalil (2000) and Kameel (2002), as:

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

Where:
ρ = Air density, kg/m3
Φ = Dependent variable.
S_{Φ} = Source term of Φ.
U, V, W = Velocity components in *x, y* and *z* coordinates directions.
$\Gamma_{\Phi,eff}$ = Effective diffusion coefficient.

The effective diffusion coefficients and source terms for the various governing differential equations are listed in table 1.

Boundary Conditions and assumptions
Four different tomb configurations were investigated; these outline the design development over the years from being merely single corridor with dead end as in tomb of Ramses VII, known as KV1 shown in figure 1 to more complicated designs of tombs KV2, KV13 and KV15.
The sky-open entrance zone is excluded from the tomb structure and free boundary conditions were assumed at entrance. The proposed ventilation floor-mounted air extract grilles locations are clearly identified in figure 1; however the visitors are omitted from these figures for clarity. These tombs volumes are then discretized using the tetrahedral tool due to the complex geometry inherent in the model. The tomb of Ramsis VII is simple in construction in a single axis; the vertical cross section clearly identified three zones, figure 1a. The entrance zone that extended to over 12 m with door locking the second zone of 20 m length that descended with steps down to another door locking the burial zone of 12 m length where the sarcophagus is located. The tomb height is 3.6 m on average and the width around 4 m on average, Khalil (2006). Figures 2 to 4 depict the various tombs geometries, extract grilles locations and tombs structure details.

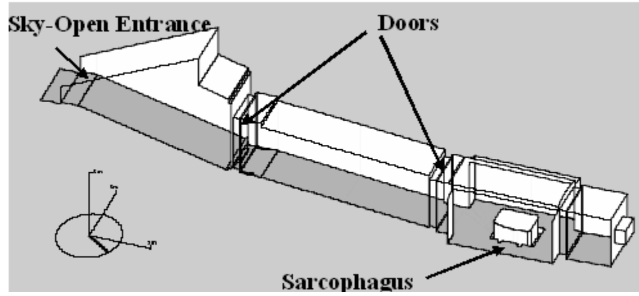

Figure 1a   KV1 with sky-open entrance

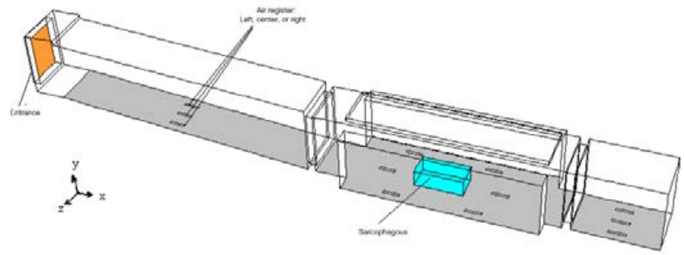

Figure 1b KV1 ventilation grilles locations

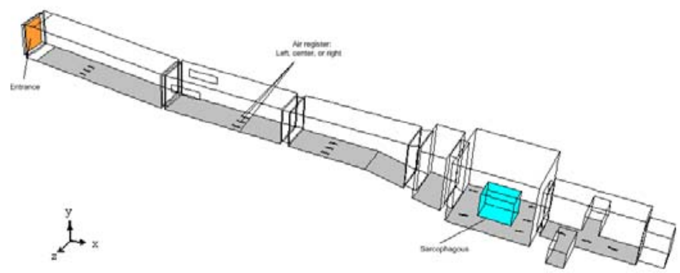

Figure 2 KV2 structure details

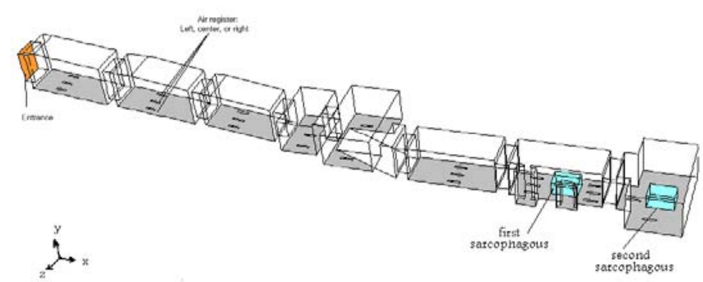

Figure 3 KV13 structure details

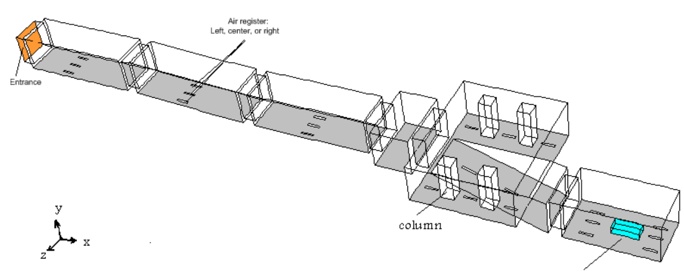

Figure 4   KV15 structure details

Over 600000 computational cells were used to map the tomb total volume .More than 1500 iterations on a PC ,using 0.3 relaxation factors were necessary to achieve the convergence criteria of residuals being less than 10^{-3} in computational time just under three hours ,for any of the tombs considered in this work and shown in figures 1 to 4 .

Inlet Air Conditions

The inlet air conditions are taken as the average day max of 40ºC (313 k) and 30% relative humidity (humidity ratio =0.0138), representing August conditions in Luxor, Egypt. As the air is admitted freely to the tomb, the turbulence intensity was assumed to be 6% and the length scale is assumed to be 1 m. However, if mechanical ventilation floor-supply option is incorporated, a smaller length scale of 0.15 m is assumed while the turbulence intensity is kept constant at 6%. Furthermore, the air is assumed to flow outward normal to the raised wooden-floor-mounted extract grilles that had the dimensions of 0.15x1.0 m along the tomb axis.

Walls

The walls are considered at a constant temperature equal to the wet bulb temperature of the outside air, which was 25ºC for Luxor Egypt. Walls were assumed to impermeable with zero species, water vapour, diffusive fluxes. The no- slip condition is enabled for all walls, while using the standard wall function for near wall treatment.

Visitors

The visitors' bodies are considered as isothermal walls kept at the human skin temperature of 37ºC due to the light clothing of the tourists in Luxor. Furthermore, it is assumed that there is no diffusive flux. The visitors' faces are considered as isothermal walls kept at the human skin temperature of 37ºC as well. Also it is assumed that there is a specified species mass fraction of 0.0411 $kg_w/kg_{d.a}$ in order to take into account the sweat effect in moisture gain to the tomb airflow, see Salama ,O.,(2008).

The tomb geometry along with the visitors' inside the tomb depicts the difficulty of using structured mesh. Therefore, the available commercial CFD code, FLUENT® 6.2, has an appropriate pre-processing tool .Furthermore, the finite difference method could not be used and hence the finite volume method should be used.

The governing equations are simultaneously solved in an iterative manner till convergence is achieved as outlined in Table 2.

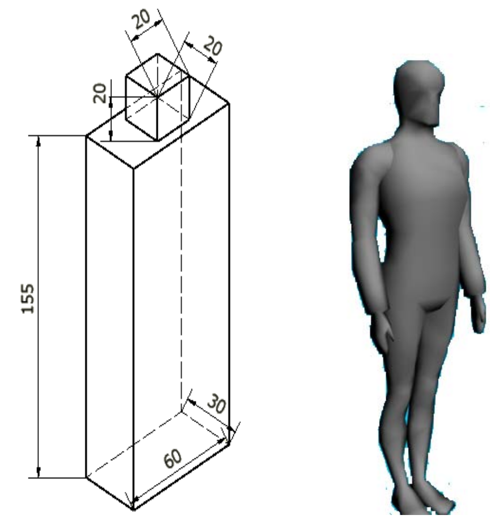

Figure 5 Visitors Modelling

Table 2: Convergence Criteria

Entity	Convergence criteria
Continuity	2.7835e-03
X-momentum, U	2.7634e-05
Y-Momentum ,V	2.0708e-05
Z-Momentum , W	2.1221e-05
Energy , H	2.1352e-07

TOMBS CLIMATIZATION CONTROL

The Egyptian government had set a handsome budget to the complete restoration of the Valley of the Kings that started years ago with the Theban Mapping Project (TMP) that fully documented the valley's tombs in contour forms and engineering as built drawings of the various individual tombs. These engineering data files are already on the Web site created by TMP (www.kv5.com). The restored tombs, more than twenty are usually open for visitors at frequent times that change depending on the time of the day and the relative humidity.

RESULTS AND DISCUSSIONS

In peruse of the appropriate ventilation system designs, simulation of actual air flow patterns and heat transfer behavior was carried out with the above computational scheme with simulation of visitors as shown in figures 6 to 17 in the following paragraphs. The proposed simulated design is to extract air through floor-mounted ports each 1.0x0.15 m at four different locations as shown in Figures 1 to 4, with air freely entering the tomb. Figure 6 depicted the predicted velocity magnitude distribution at the middle plane showing 24 visitors located along the tomb length.

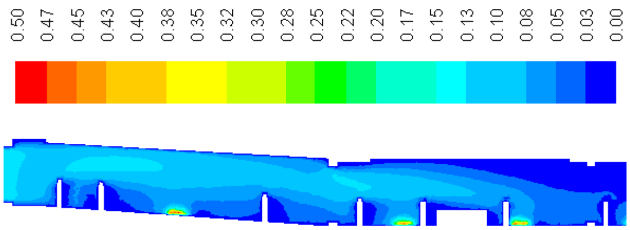

Figure 6 Predicted velocity contours, m/s, KV1

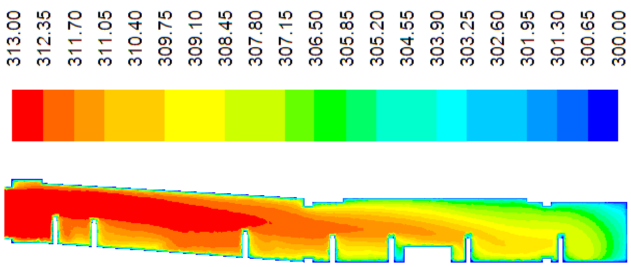

Figure 7 Predicted temperature contours, K, KV1

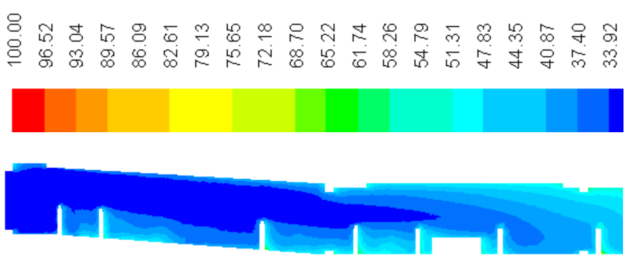

Figure 8 Predicted Relative Humidity, %, KV1

These visitors are located in the most likely positions where tomb paintings are to be viewed .Consider that the air velocity in the tomb should not exceed 0.12 m/s in order not to create any undesired drafts. Figure 6 indicated that this limit is satisfied. It is very interesting to observe the higher velocities in the middle section of the tomb as a result of the reduction of the void height. The proposed simulated design incorporated extract air through floor-mounted ports at four locations. The predicted velocity contours indicated that velocities in the vicinity of the floor mounted extracting grilles are higher than 0.12 m/s while in the rest of the domain the values are generally less than 0.12 m/s and particularly in the wall vicinity. The isotherms contours clearly demonstrate the extent of the ambient outside warm air penetrating the tomb environment up to 50% of the length where temperatures are 313 K. The corresponding relative humidity contours are shown in Figure 8, identifying dangerous high levels at the end of the tomb. Excessive humidity causes damage and deterioration of artifacts and paintings. In the work of Osama (2008), Abdel Aziz (2005), Khalil et al (2006) and Khalil (2007), the effect of number of visitors was investigated and the present paper shows the case with a minimum of 24 visitors.

The second example is that of KV2, the tomb of Ramsis IV, it had the same geometrical configurations as KV1, but with a length of 88 m. Figures 9 to 11 demonstrates the predicted velocity, temperature and relative humidity contours for KV2 with 27 visitors. Velocities are lower than in KV2 as 11 extraction grilles were utilized in the centre of the tomb along its axis.

KV13 is the tomb and burial place of the noble Bay of the Nineteenth Dynasty. The tomb was later reused by Amenherkhepshef and Mentuherkhepsef of the Twentieth Dynasty.

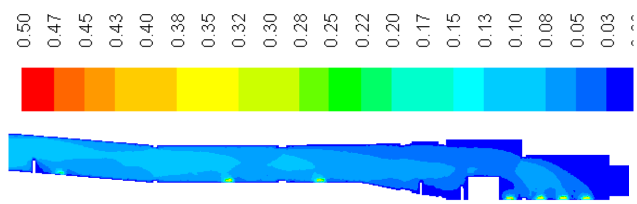

Figure 9 Predicted velocity Contours m/s, KV2

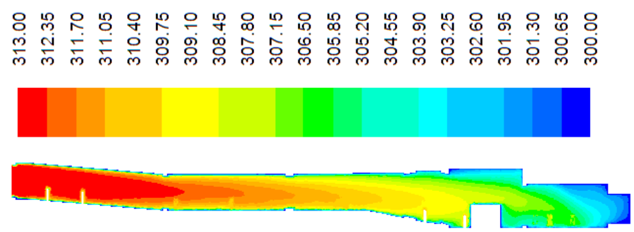

Figure10 Predicted Temperature Contours, K, KV2

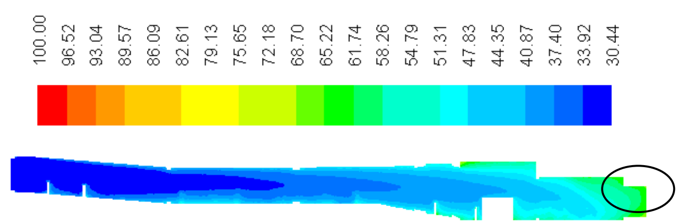

Figure11 Predicted Relative Humidity, %, KV2

The tomb geometrical design is different than that of KV1 and KV2 as it is longer with many intermediate chambers as was shown earlier in Figure 3.The corresponding velocity, temperature and relative humidity contours are shown in Figures 12 to 14 respectively, with 9 floor-mounted extraction grilles .For further details of the effect of using side grilles, reference should be made to Osama (2008).

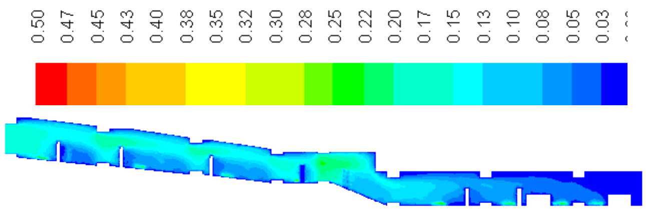

Figure 12 Predicted velocity Contours, m/s KV13

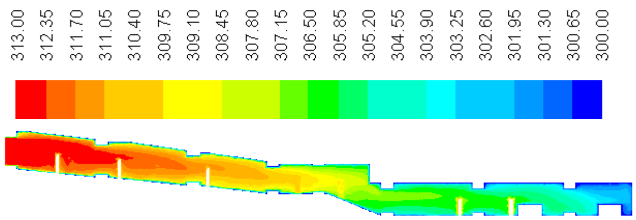

Figure 13 Predicted temperature Contours, K, KV13

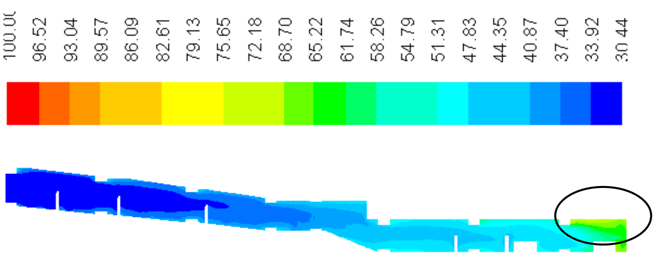

Figure 14 Predicted Relative Humidity, %, KV13

The fourth tomb is that of King Siti II, known as KV15, the tomb had intermediate hall with columns followed by a sloped ramp to the sarcophagus. The complexity of the tomb necessitated the typical use of larger number of about 700000 tetrahedral cells. The obtained computations were based on the above assumptions with a base case of 26 visitors distributed in the tomb as shown in Figures 15, 16 and 17. Velocities were only above 0.12 m/s near the raised floor at the extract locations.

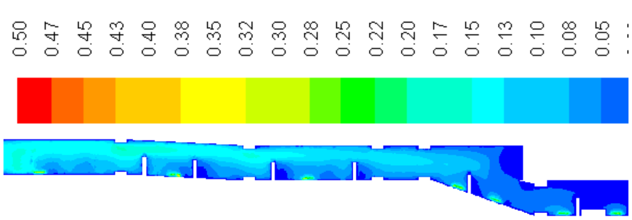

Figure 15 Predicted velocity Contours, m/s KV15

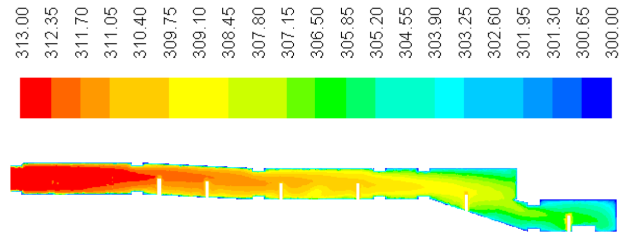

Figure 16 Predicted temperature Contours, K, KV15

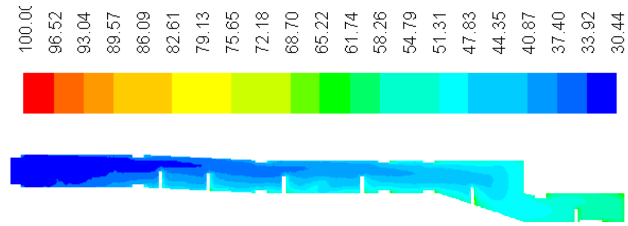

Figure 17 Predicted Relative Humidity, %Rh, KV15

The corresponding isothermal lines are shown in Figure 16 for a wall temperature of 295 K. The effect of the fresh incoming hot air of 40 ^{0} C was dominant to almost 25% of the tomb length in the core area. Temperatures generally cools off to nearly 29 ^{0} C. Away from the centre plane temperatures cool down to near 300 K as shown in Figure 16. Predicted relative humidity contours shown in Figure 17 indicated that excessive humidity towards the dead end of the tomb which can be easily attributed to the produced water vapor from human activities and not outside humidity that is only 30% during August. Other investigations were carried out by Osama (2008) to explore the effects of the number of visitors, proposed extraction rates and locations of extract grilles.

DISCUSSION AND ANALYSES

The main flow pattern of the free supplied air and floor mounted extracts is slightly influenced by the extraction ports locations, for KV1 and KV2. For each visitor group location, a corresponding proper airside design was suggested to provide the optimum utilization of the supplied air.

The optimum utilization of the air movement to ventilate and reduce temperature can be attained by locating the extraction ports to minimize the recirculation zone and prevent the air short circuits. Ideally, the optimum airside design system can be attained, if the airflow is directed to pass all through the tomb enclosure areas before being extracted.

Still all shown predictions clearly indicated the usefulness of raised-floor extracts that do not disturb the archeological value of the tomb and do not install any artificial materials in the tombs. The influence of the recirculation zones on the visitors' occupancy zone and also on the fresh supplied air was investigated and low velocity values were observed and were well below the ASHRAE recommended values.

The effect of number of visitors was found to be strong as they are the source of water vapor production due to perspiration. The obtained numerical computations were rerun with smaller number of visitors, typically 8, the two following figures 18 and 19 clearly show that effect. The yellowish areas (higher humidity) were less shown in Figure 19 for the smaller number of visitors of 8 instead of 26 of the base case. It should be emphasized that the detailed velocity profiles in the tombs were obtained at various locations and those helped in assessing the viability of the proposed ventilation designs.

More numerical results can be seen in the work of AbdelAziz (2005) and Salama (2008).

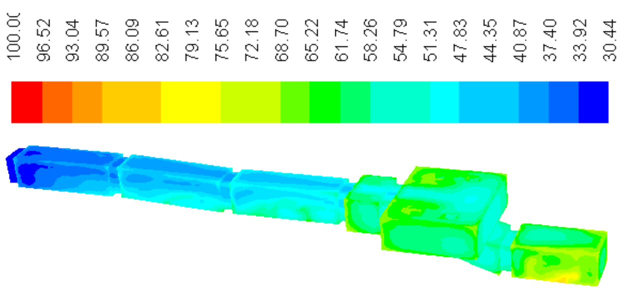

Figure 18 Predicted Contours of relative humidity for KV15 with 26 visitors

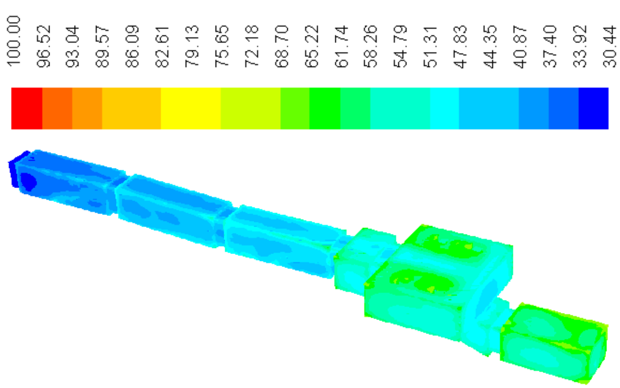

Figure 19 Predicted Contours of relative humidity for KV15 with 8 visitors

CONCLUSIONS

To reach optimum airside system design, the proper air conditioned set point should be selected close to the average wall temperature in order to minimize the temperature gradient near the wall. This setup is important as a preservation procedure for the tomb artifacts. Future work should include comprehensive investigations of the humidity effect in order to achieve the recommended operating climatic conditions for the tomb. The present research program would ultimately indicate the maximum allowed simultaneous number of visitors in the tomb so that the air relative humidity and air quality should be maintained at the recommended levels to preserve the artifacts.

REFERENCES

AbdelAziz, O., 2005 "Flow Regimes, Thermal and Humidity Patterns in Ventilated Archaeological Tombs", MSc Thesis, Cairo University.

Abdel-Aziz, O. and Khalil ,E.E., 2005 ," Modeling Of Indoor Air Quality And Comfort In The Tombs Of Valley Of Kings , 2005 ASME Summer Heat Transfer Conference, Paper HT2005-72005 , July 2005, San Francisco, California, USA.

Abdel-Aziz, O. and Khalil, E.E., 2005, "Predictions Of Air Flow Patterns And Heat Transfer In The Tombs Of The Valley Of The Kings "Proceedings, CLIMA, October 2005, Paper 358.

ASHRAE Handbook, Fundamentals 2005, ASHRAE, Atlanta, USA.

Cho, Y., Awbi, H. B., and Karimipanah, T., 2002, "A comparison between four different ventilation systems", ROOMVENT 2002, 181-184.

FLUENT, 6.2.Fluent Inc., 2005

Kameel, R., 2002, Computer aided design of flow regimes in air-conditioned operating theatres, Ph.D. Thesis work, Cairo University.

Kameel, R., and Khalil, E. E., 2003, Energy efficiency, air quality, and comfort in air-conditioned spaces, DETC2003 / CIE – 48255, ASME 2003, Chicago, Illinois USA, 2003.

Khalil, E. E., 2000, Computer aided design for comfort in healthy air conditioned spaces, Proceedings of Healthy Buildings 2000, Finland, Vol. 2, PP. 461-470.

Khalil, E.E. and Abdel-Aziz, O., 2006, "A Dry Passage to the Afterlife" FLUENT NEWS, 2006, PP28.

Khalil, E.E., 2006," Preserving the Tombs of the Pharaohs", ASHRAE JOURNAL, December 2006, PP.34-38.

Khalil, E.E. 2007,"Flow Regimes and Thermal

Patterns in 15th Century BC Tombs of the Valley Of Kings", Proceedings 2nd ME-EE Conference, Greece, May 2007.

Khalil, E.E., 2007," Air Flow Patterns and Thermal Behavior in "King Tutankhamen Tomb", International Review of Mechanical Engineering, IREME July Issue, Vol 1 n° 4, pp 444- 450. , 2007

Khalil, E.E., 2007" Air Flow Regimes and Thermal Patterns in the Tombs of Valley of Kings", Proceedings, 38th International Congress on Heating, Refrigerating & Air-Conditioning, Belgrade, December V2007

Khalil, E.E., 2008," Air Flow Regimes and Thermal Patterns in the Tombs in Valley Of Kings", 10th Global Engineering Conference, April 2008, Las Vegas, USA.

Salama ,O.,2008 "Flow, Thermal Patterns And Moisture Distributions In Ventilated Archaeological Tombs, Valley Of Kings, Luxor, MSc. Thesis, Cairo University,

Stoecker, W. F., and Jones, J. W., 1985, Refrigeration and air conditioning, Second Edition, TATA McGraw-Hill Publishing Company LTD., 1985.

Weeks, K., 1999, Theban Mapping Project, AUC, Egypt.

Table 1: Terms of Partial Differential Equations

	Φ	$\Gamma_{\Phi,eff}$	S_Φ
Continuity	1	0	0
X-momentum	U	μ_{eff}	$-\partial P/\partial x + \rho g_x + S_U$
Y-momentum	V	μ_{eff}	$-\partial P/\partial y + \rho g_y + S_V$
Z-momentum	W	μ_{eff}	$-\partial P/\partial z + \rho g_z(1+\beta\Delta t) + S_W$
H-equation	H	μ_{eff}/σ_H	S_H
RH-Equation	RH	μ_{eff}/σ_{RH}	S_{RH}
τ-age equation	τ	μ_{eff}/σ_τ	ρ
k-equation	k	μ_{eff}/σ_k	$G - \rho\,\varepsilon$
ε-equation	ε	$\mu_{eff}/\sigma_\varepsilon$	$C_1\,\varepsilon\,G/k - C_2\,\rho\,\varepsilon^2/k$

$\mu_{eff} = \mu_{lam} + \mu_t$ $\quad\quad \mu_t = \rho\,C_\mu\,k^2/\varepsilon$

$G = \mu_t\,[2\{(\partial U/\partial x)^2 + (\partial V/\partial y)^2 + (\partial W/\partial z)^2\} + (\partial U/\partial y + \partial V/\partial x)^2 + (\partial V/\partial z + \partial W/\partial y)^2 + (\partial U/\partial z + \partial W/\partial x)^2]$

$S_U = \partial/\partial x(\mu_{eff}\,\partial\Phi/\partial x) + \partial/\partial y(\mu_{eff}\,\partial\Phi/\partial x) + \partial/\partial z(\mu_{eff}\,\partial\Phi/\partial x)$

$S_V = \partial/\partial x(\mu_{eff}\,\partial\Phi/\partial y) + \partial/\partial y(\mu_{eff}\,\partial\Phi/\partial y) + \partial/\partial z(\mu_{eff}\,\partial\Phi/\partial y)$

$S_W = \partial/\partial x(\mu_{eff}\,\partial\Phi/\partial z) + \partial/\partial y(\mu_{eff}\,\partial\Phi/\partial z) + \partial/\partial z(\mu_{eff}\,\partial\Phi/\partial z)$

$C_1 = 1.44,\ C_2 = 1.92,\ C_\mu = 0.09$

$\sigma_H = 0.9,\ \sigma_{RH} = 0.9,\ \sigma_\tau = 0.9,\ \sigma_k = 0.9,\ \sigma_\varepsilon = 1.225$