

## CFD-CONTROLLED CLIMATE DESIGN OF THE ARCHEOLOGICAL TOMBS OF VALLEY OF KINGS"

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**Abstract** *Airflow characteristics in ventilated and air-conditioned spaces play an important role to attain comfort and hygiene conditions. This paper utilizes a 3D Computational Fluid Dynamics (CFD) model to assess the airflow characteristics in ventilated and air-conditioned archeological tombs of Egyptian Kings in the Valley of the Kings in Luxor, Egypt. It is found that the optimum airside design system can be attained, if the airflow is directed to pass all the enclosure areas before the extraction with careful selection of near wall velocities to avoid any wear or aberration of the tomb-wall paintings. Still all factors and evaluation indices have the shortage to describe the influence of the recirculation zones on the occupancy zone of the visitors and also on the fresh supplied air. The mode of evaluation should assess the airflow characteristics in any tomb passage according to its position in the enclosure and the thermal pattern and air quality.*

**Keywords:** *CFD, Archeological Tombs, Indoor air Quality*

### 1. 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 identified 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” Cho et al(2002). For the present work, following other earlier similar work Khalil (2000) , Kameel (2002) and Kameel and Khalil (2003), 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. The present paper introduces a description of the computational solver and its validation with steady state results of the previous properly related literatures. Basically, airside design types are considered here for the tomb passage of King Ramsis VII, including different visitors (obstacles) alternative positioning to introduce the capability of the design to provide the optimum characteristics.

The full description of the parametric cases' parameters is discussed later. The primary objective of the present work is to assess the airflow characteristics, thermal pattern and energy consumption in the different tomb ventilation configurations in view of basic known flow characteristics. The paper ends with a brief discussion and conclusion.

## 1.1. Problem Formulation

The proper tactical airflow distribution is required in all applications in the tomb of Ramsis VII which is of simple single axis passage. The airflow distribution in its final steady pattern is a result of different interactions such as, the airside design, objects distribution, thermal effects, occupancy movements, etc. The airside design and internal obstacles are the focus of the present work. The free air supply and mechanically extracted ducted air play an important role in the main flow pattern and the creation of main recirculation zones. The internal obstacles can offend the airflow pattern by different ways, such as, by increasing the recirculation zones or by deflecting the main airflow pattern.

## 2. METHOD DESCRIPTION

### 2.1 Model Equations

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

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

Where:

$\rho$  = Air density, kg/m<sup>3</sup>  $\Phi$  = Dependent variable.

$S_{\Phi}$  = Source term of  $\Phi$ .  $U, V, W$  = Velocity vectors.

$\Gamma_{\Phi, \text{eff}}$  = Effective diffusion coefficient.

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

**Table 1: Terms of Partial Differential Equations**

	$\Phi$	$\Gamma_{\Phi, \text{eff}}$	$S_{\Phi}$
Continuity	1	0	0
X-momentum	U	$\mu_{\text{eff}}$	$-\partial P / \partial x + \rho g_x + S_U$
Y-momentum	V	$\mu_{\text{eff}}$	$-\partial P / \partial y + \rho g_y + S_V$
Z-momentum	W	$\mu_{\text{eff}}$	$-\partial P / \partial z + \rho g_z(1 + \beta \Delta t) + S_W$
H-equation	H	$\mu_{\text{eff}} / \sigma_H$	$S_H$
RH-Equation	RH	$\mu_{\text{eff}} / \sigma_{RH}$	$S_{RH}$
$\tau$ -age equation	$\tau$	$\mu_{\text{eff}} / \sigma_{\tau}$	$\rho$
k-equation	k	$\mu_{\text{eff}} / \sigma_k$	$G - \rho \epsilon$
$\epsilon$ -equation	$\epsilon$	$\mu_{\text{eff}} / \sigma_{\epsilon}$	$C_1 \epsilon G / k - C_2 \rho \epsilon^2 / k$

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

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

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

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

$$\mu_{\text{eff}} = \mu_{\text{lam}} + \mu_t \quad \mu_t = \rho C_{\mu} k^2 / \epsilon \quad C_1 = 1.44, \quad C_2 = 1.92, \quad C_{\mu} = 0.09$$

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

### 3. THEBAN CLIMATIZATION CONTROL PROJECT

#### 3.1. General

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. The restored toms, more than twenty are usually open for visitors at frequent times that change depending on the time of the day and the relative humidity. Attempts were made to systematically investigate and assess the flow pattern, heat transfer and relative humidity in these tombs. The present work preliminary attempts to investigate the flow field in the tomb of Ramsis VII ;the tomb is simple in construction in a single axis as shown here in Figure 1a, where the top is the plan and the vertical cross section at the bottom clearly identified three zones. The entrance zone that extended to over 12 m with door locking the second zone that descended with steps down to another door locking the burial zone where the sarcophagus is located. Figure 1b shows a photographic view of the sarcophagus zone.

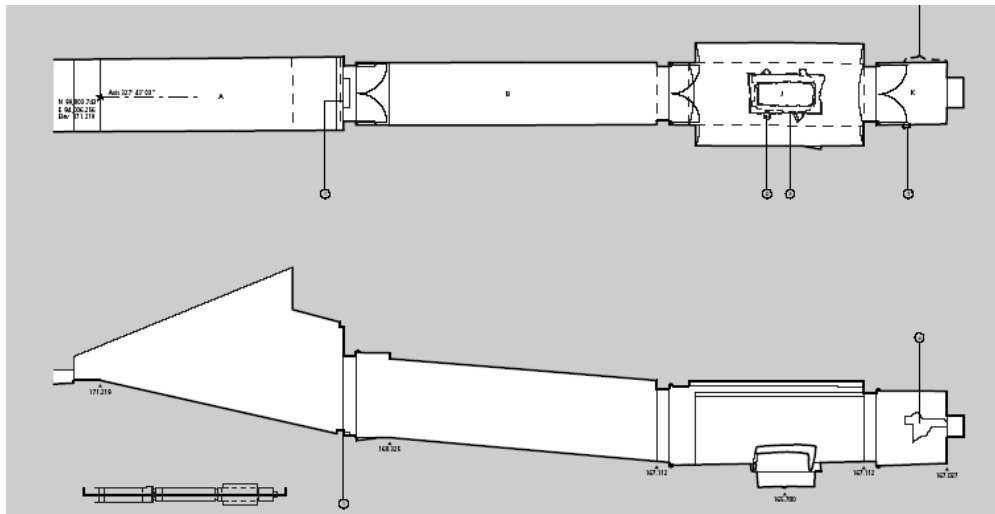


Figure 1a: Tomb of Ramsis VII Configuration, Weeks (1999)



Figure 1b: Ramsis VII Tomb interior

### 3.1 Computational Results

Over 420000 computational cells were used to map the tomb total volume of  $618 \text{ m}^3$ , the maximum computational volume was  $4.823679\text{e-}03 \text{ m}^3$  and the minimum volume was  $7.416266\text{e-}05 \text{ m}^3$ . The minimum cell-face area:  $.00229 \text{ m}^2$ , the maximum being  $0.0626 \text{ m}^2$ . More than 500 iterations were necessary to achieve the convergence criteria of residuals being less than  $10^{-3}$  in computational time just under three hours, figure 2. The two-equation turbulence model yielded poorer results than those of the Large Eddy Simulations which were used here.

## 4. 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 simulating visitors as shown in figures 3 to 8 at wall temperature of 295 K. The proposed simulated

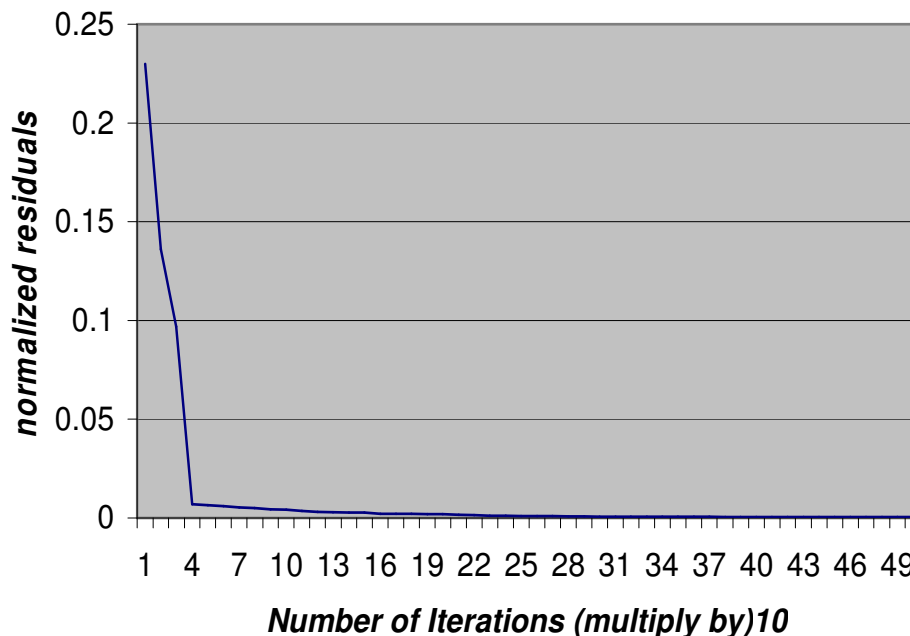


Figure 2: Maximum normalized residuals in governing equations

design is to extract air through floor-mounted ports each  $1.0 \times 0.15 \text{ m}$  at four different locations as shown in Figure 5, with air freely entering the tomb. Figure 3 depicted the predicted velocity vectors distribution in a horizontal plane at 1 m showing 33 visitors located along the tomb passage. These 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  $0.12 \text{ m/s}$  in order not to create any undesired drafts. Figure 4 indicated that this velocity 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.

Figure 5 indicated that the near wall velocities attain very low values, typically less than  $4 \times 10^{-4} \text{ m/s}$ . Such values are very important to ensure that air flow would not result in wear of wall paintings. The isovelocity contours are shown in Figure 6 at Y-Z plane in the sarcophagus middle,  $X=36.2 \text{ m}$ . The corresponding isothermal lines are shown in Figure 7 below for a wall temperature of 295 K. The effect of the fresh incoming hot air of  $37^\circ \text{ C}$  was dominant to almost 45% of the tomb length in the core area. Temperatures generally cool off to nearly  $29^\circ \text{ C}$ . Away from the centre plane temperatures cool down to near 296 K. The

corresponding air temperature contours at a Y-Z plane in the middle of the sarcophagus are shown here in Figure 8. The uneven distribution is attributed to the unsymmetrical nature of the tomb configuration.

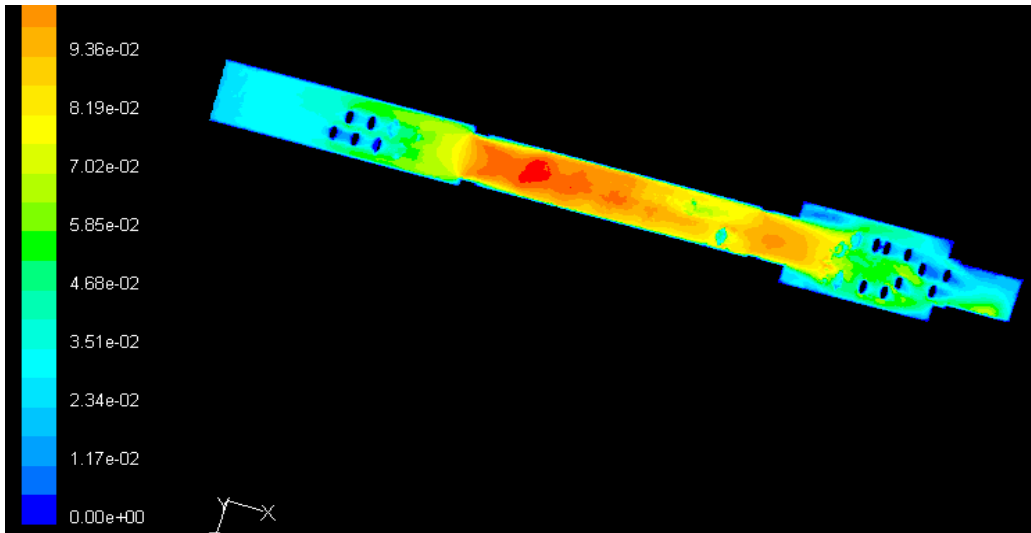


Figure 3: Predicted Velocity vectors contours at 1 m above ground, m/s,

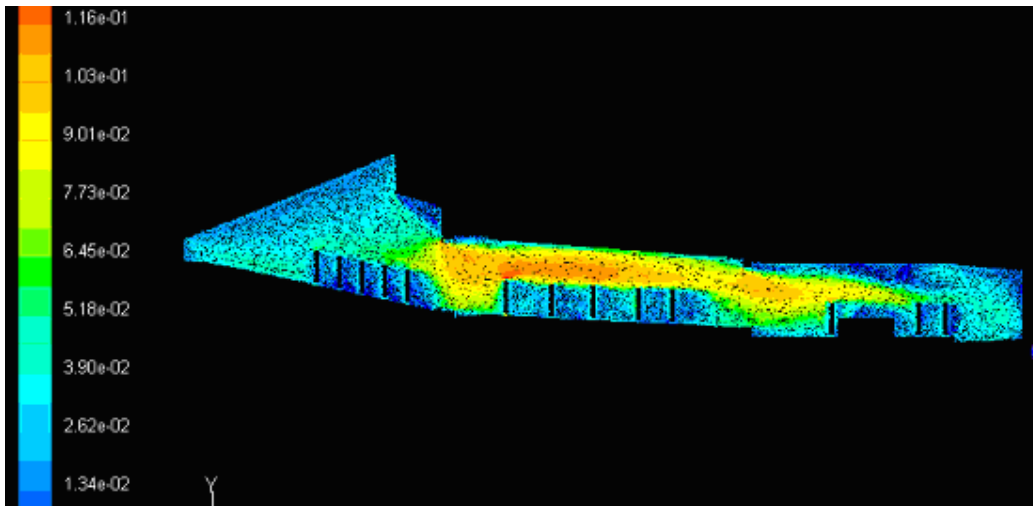


Figure 4: Predicted Velocity vectors distribution at middle plane, m/s.

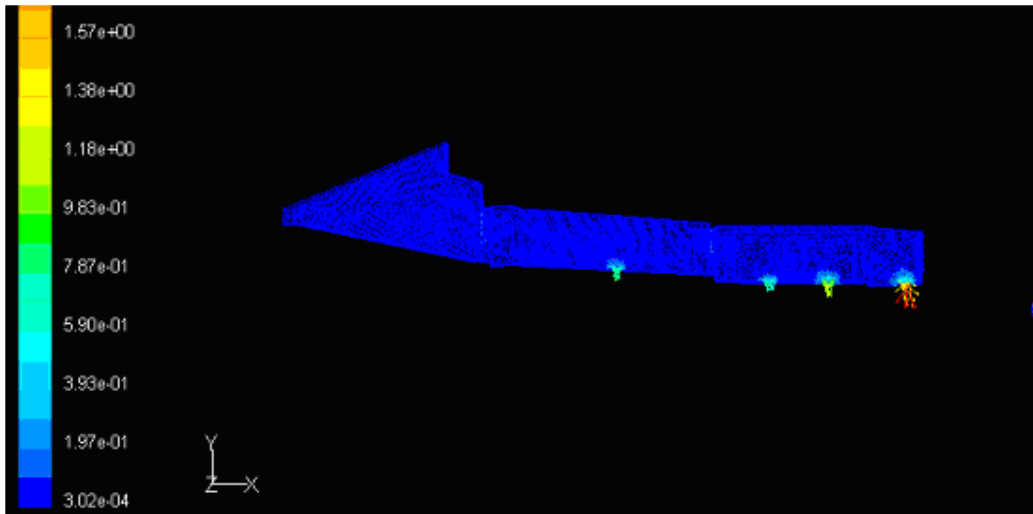


Figure 5: Predicted Wall-Vicinity air Velocity distributions, m/s

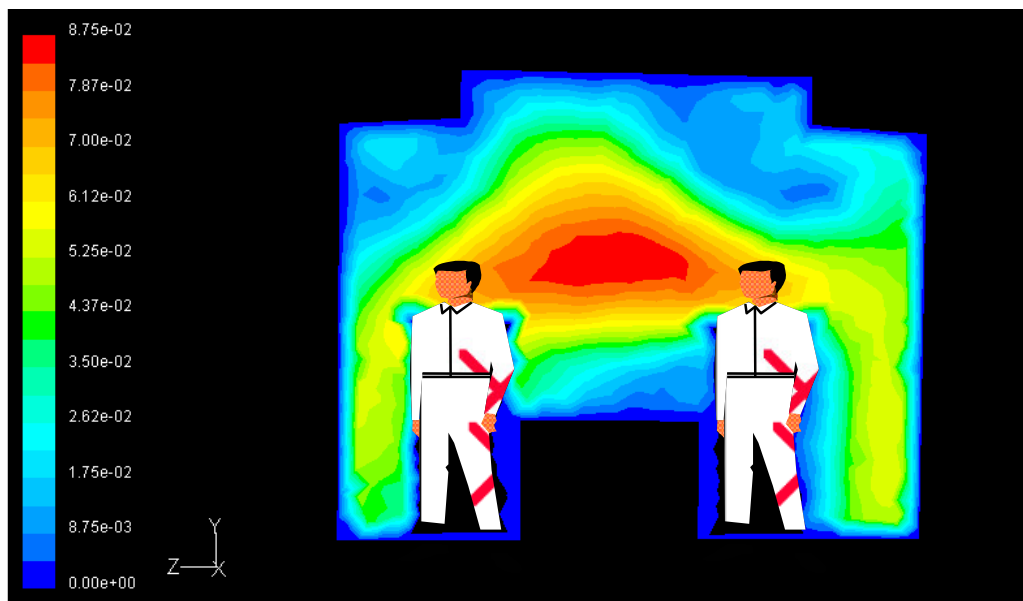


Figure 6: Predicted Iso-Velocity contours, m/s, at Y-Z plane at sarcophagus middle.

## 5. SUMMARY AND CONCLUSIONS

The main flow pattern of the free supplied air and floor mounted extracts is slightly influenced by the extraction ports locations. For each visitor group location, a corresponding proper airside design is 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 the enclosure areas before the extraction.

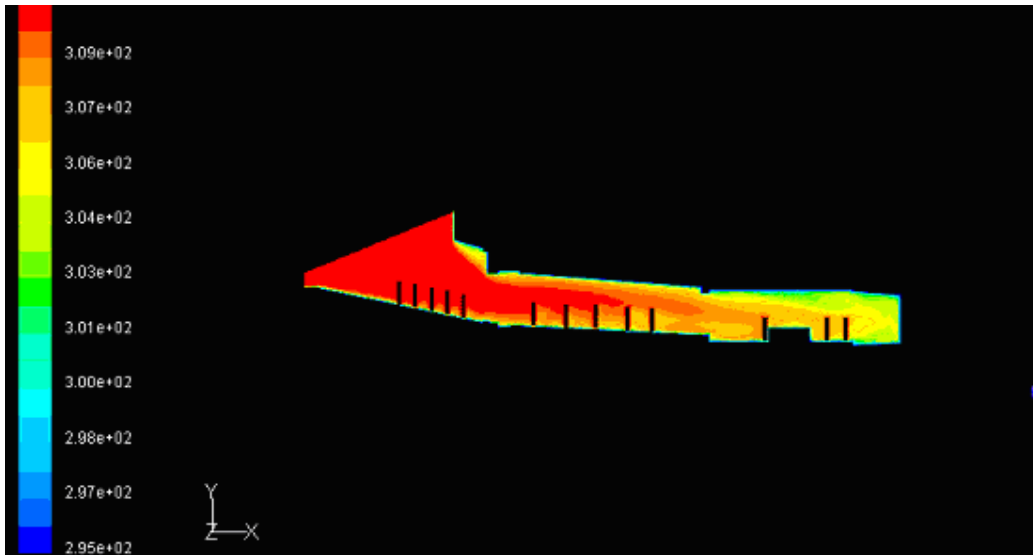


Figure 7: Predicted Temperature distribution at X-Y middle plane,  $T_w=295K$ .

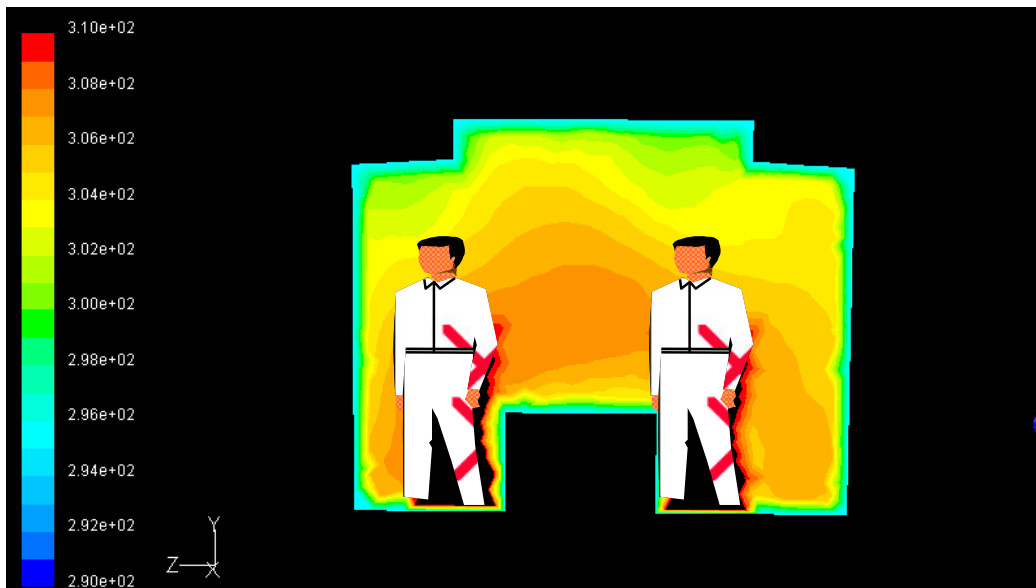


Figure 8: Predicted isothermal contours at a plane at sarcophagus middle.

Still all shown predictions clearly indicated the usefulness of floor extracts that do not disturb the archeological value of the tomb and do not install any artificial materials in the tombs.

## 6. RECOMMENDATIONS

Optimum airside design system can be attained, if the airflow is directed to pass all the enclosure areas before being extracted. The model of evaluation should assess the airflow characteristics in any enclosure according to its position in the enclosure and the expected number of visitors that may affect the air during its pass to the extract ports.

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