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Computational Analysis of Airflow Distribution inside Mevlana Museum

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ABSTRACT: In this study, Computational Fluid Dynamics (CFD) has been employed to examine the air flow distribution inside Mevlana museum which is one of the important historical places in Turkey. The continuity, momentum and energy equations together with the k-ε turbulence model have been solved using a commercial CFD package. Steady and incompressible flow assumptions have been made to simplify the simulation and reducing the computation time. Sample of the velocity vector plots at different distances from the ground floor of the museum showed circulation zones and vortices at some areas indicating poor air refreshment and possible contaminant emissions. Low velocity areas are also noticeable in some places particularly behind the pillars and any flow obstructs. The dome was found to be a source of enhancing the air flow distribution and flow motion inside the museum. The study concluded that the natural air flow distribution can be improved by different combinations of opening windows and doors based on the wind speed and direction.

Key words: Mevlana museum airflow, Museum flow distribution, Building CFD flow

Mevlana Müzesi İçinde Hava Akımı Dağılımının Hesaplamalı Analizi

ÖZET: Bu çalışmada, Hesaplamalı Sıvı Dinamiği (HSD=CFD), Türkiye'deki önemli tarihi yerlerden birisi olan Mevlana Müzesi'ndeki hava akımı dağılımını araştırmak için kullanılmıştır. Devamlılık, moment ve enerji eşitlikleri ile birlikte k-ε türbülans modeli, ticari CFD paket programı kullanılarak hesaplanmıştır. Durağan ve akışkan akım tahminleri, simülasyonu basitleştirmek ve hesaplama zamanının azaltmak amacıyla yapılmıştır. Müze zemininden farklı mesafelerdeki örnek hız vektör parselleri, sirkülasyon alanları ve bazı girdaplarda zayıf hava tazelenmesini ve muhtemele kirli emisyonlara işaret etmiştir. Özellikle sütün arkaları ve akım engelleyiciler gibi bazı alanlarda düşük hava hız alanları gözlemlenmiştir. Kubbenin müze içerisindeki hava akımını ve hareketini iyileştirici bir kaynak olduğu bulunmuştur. Araştırmada, doğal hava akımının, rüzgar hız ve yönüne bağlı olarak faklı kombinasyonlarda pencere ve kapı açılış kombinasyonları ile iyileştirilebileceği sonucuna varılmıştır.

Anahtar kelimeler: Mevlana Müzesi hava akımı, Müze akış dağılımı, Yapı CFD akışı

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Introduction

In the previous times, while constructing buildings, builders didn't have tool to evaluate the ventilation and airflow distribution inside the building for better environmental conditions. Some of those buildings are now historical monuments which keep many artefacts inside, and also open for thousands of visitors every day. Culture and tourism ministry are starving to conserve the monument and the artefacts in good conditions. Moreover, standard air ventilation has to be fulfilled for visitors comfort and to improve Indoor Air Quality IAQ which has been investigated in several studies (Hummelgaard et. al, 2007; Stavrakakis et. al, 2010). According to ASHRAE Standard 55-1992 standard for thermal comfort (ASHRAE, 1992) air temperature has to be between 20 and 27^{o} C and a relative humidity between 30% and 60%. And yet controlling the temperature and humidity using HVAC system can be damaging the monument and the artefacts.

Museum authority can only try to use natural ventilation with minimum use of heating and cooling systems. A large number of governing factors affect natural ventilation of buildings, such as weather condition on site, building structure, the heat sources, the envelope conductance, solar radiation and so on. Thus natural ventilation design is integrated with weather, environment and building (Zhang and Guan, 2006).

The ventilation system uses outdoor air during daytime to remove the heat gains and indoor contaminant emissions. Engineering experience and field studies indicate that an outdoor air supply of about 10 L/s per person is very likely to provide acceptable perceived indoor air quality in office spaces, whereas lower rates may lead to increased sick building syndrome symptoms (Apte et al., 2000; Mendell, 1993). The minimum ventilation rates and other measures intended to provide indoor air quality that is acceptable to human occupant and that minimize adverse health effects have been standardized (ASHRAE, 2013).

The ventilation system should not only designed to provide the necessary amount of outdoor air but also to have it well distributed to avoid local contamination and to scavenging indoor air and allowing fresh air to be well distributed. Moreover, The good ventilation increases the occupant’s thermal comfort by moving air with a maximum indoor air velocity of approximately 2 m/s (Givoni, 1998).

Natural ventilation relies on the wind and the “chimney effect”. When the wind moving along a wall it creates a vacuum that pulls air out of the windows. The chimney effect occurs when cool air enters a home on the first floor or basement, absorbs heat in the halls, rises, and exits through the dome windows. This creates a partial vacuum, which pulls more air in through lower-level windows. The wind will naturally ventilate the museum by entering or leaving windows and doors, depending on their orientation relative to the wind. When wind blows against the opened doors or windows, air is forced to enter. However, a windbreak—like a fence, hedge, or row of trees that blocks the wind can force air either into or away from nearby windows.

Chung and Hsu (2001) investigated the ventilation efficiency of different natural ventilation patterns arranged by two inlets and two outlet diffusers at different locations with a full-scale test chamber. The results indicate that the locations of window openings severely influence the natural ventilation efficiency in rooms. The airflow distribution, the carbon dioxide concentration, and the air change rate were investigated for various window opening angles and inlet air velocities. The simulated and experimental results reveal the typical ventilation characteristics of a center-pivoting window and will allow designers to specify appropriate window opening angles for different outdoor airflow velocities (Chou et al., 2008).

In this work, all study has been carried out using CFD to simulate the airflow distribution inside Mevlana museum under steady conditions considering the windows and doors those are opened during the visits. Humidity, emitted gas distributions have not been taken into account which is not less important than air distribution.

Mathematical Model

The air flow distributions inside the museum were identified by solving the fluid flow governing equations using the Eulerian approach. Reynolds Average Navier Stokes, RANS, equations, together with the continuity and energy equations. The turbulent k-ε model has been implemented to estimate the Reynolds stress terms. The commercial CFD package STARCCM+ used in this study. The equations employed in the model are as follow:

Continuity Equation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho U_j\right)=0 \tag{1}$$

Reynolds Average Navier Stokes (Momentum) Equations

$$\frac{\partial \rho U_i}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho U_i U_j\right)=-\frac{\partial p'}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu_{eff}\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)\right]+S_M \tag{2}$$

Reynolds Average Energy Equation

$$\frac{\partial \rho h_{tot}}{\partial t}-\frac{\partial p}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho U_j h_{tot}\right)=$$

$$=\frac{\partial}{\partial x_j}\left(\lambda\frac{\partial T}{\partial x_j}+\frac{\mu_t}{\mathrm{Pr}_t}\frac{\partial h}{\partial x_j}\right)+\frac{\partial}{\partial x_j}\left[U_i\left(\tau_{ij}-\rho\overline{u_i u_j}\right)\right]+S_E \tag{3}$$

***k-ε* Turbulence Equations**

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho U_j k\right)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+P_k-\rho\varepsilon+P_{kb}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho U_j\varepsilon\right)=$$

$$=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+\frac{\varepsilon}{k}\left(C_{\varepsilon1}P_k-C_{\varepsilon2}\rho\varepsilon+C_{\varepsilon1}P_{\varepsilon b}\right) \tag{4}$$

The term P_{kb}=0 as the effect of buoyancy has been neglected

Pressure fluctuations and turbulent viscosity can be calculated from the following equations.

$$p'=p+\frac{2}{3}\rho k+\frac{2}{3}\mu_{eff}\frac{\partial U_k}{\partial x_k}$$

$$\mu_t=C_\mu\rho\frac{k^2}{\varepsilon}; \tag{5}$$

Where;

$$\mu_{eff}=\mu+\mu_t \tag{6}$$

$$P_k=\mu_t\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)\frac{\partial U_i}{\partial x_j}-\frac{2}{3}\frac{\partial U_k}{\partial x_k}\left(3\mu_t\frac{\partial U_k}{\partial x_k}+\rho k\right) \tag{7}$$

All the constants are shown in Table 1

Table 1 The value of the constant used in k-ε model

$C_{\varepsilon 1}$	*k-ε* turbulence model constant	1.44
$C_{\varepsilon 1 \mathrm{RNG}}$	RNG *k-ε* turbulence model coefficient	$1.42-f_h$
$C_{\varepsilon 2}$	*k-ε* turbulence model constant	1.92
$C_{\varepsilon 2 \mathrm{RNG}}$	RNG *k-ε* turbulence model constant	1.68
C_μ	*k-ε* turbulence model constant	0.09

Model Preparation and Meshing

Using the original 2-D drawings provided by the museum authority, the 3-D CAD of the museum has been constructed using SolidWorks 2013 from as shown in Figure 1. The tombs, tables and interiors have been simplified and included into the CAD model. The model also includes a number of 430 people distributed over the museum floor based on observations as shown in Figure 2.

The number of people was calculated based on the average daily visitors of 10500 (minimum of 4000, and maximum of 17000) in 8 hours, assuming each visitor spent 20 minutes inside the museum. The CAD is then imported into the CFD package for re-meshing and performing the air flow analysis. The number of volume cells used in the model is approximately 3 millions. The simulation was carried out on i7 processor and 16 GB RAM laptop. Figure 3 shows the final CAD after using the volume mesh.

Weather wind speed and outdoor temperature have been calculated as a monthly average values over 4 years 2010-2013 from Turkish State Meteorological Service in Konya City in Turkey, as shown in Figure 4. The wind speed has been corrected to the reference measure height using the following equations which take into account the wind boundary layer.

$$U/U_o = (z/z_o)^B \qquad (8)$$

U is the wind speed at a height z while U_o is the speed corresponds to a measurements height z_o. The value of B was taken as 1/7. In fact the value B depends on weather stability and surface roughness. Moreover surrounding to the museum such as buildings and trees can change dramatically the airflow direction and magnitude due to the associated vortices.

The wind direction variations for 12 months over the last 4 years have also been provided. The current study was carried out during the month of July where temperature is maximum and expected to be the most uncomfortable time for visitor. Based on the most probable direction of the wind during this month, the normal velocity of the air at the opened windows and doors have been calculated to estimate the mass flow rate. People body is considered isothermal surface with a temperature of 37^oC.

As the museum walls and ceiling is thick, it is not expected to have a significant heat transfer; therefore, an adiabatic wall temperature is assumed. However, more accurate results may be obtained if the temperature of the walls and particularly the ceiling are known (Roger et al., 1987).

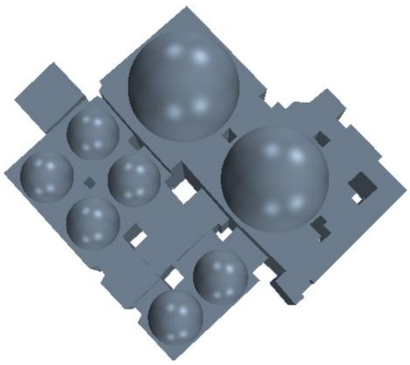


Figure 1. 3-D CAD of Mevlana Museum

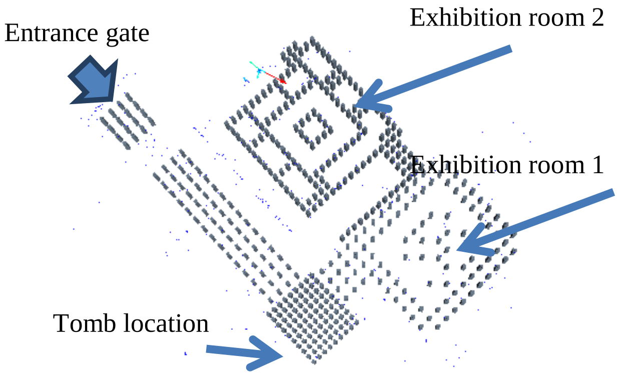


Figure 2. Visitors distribution

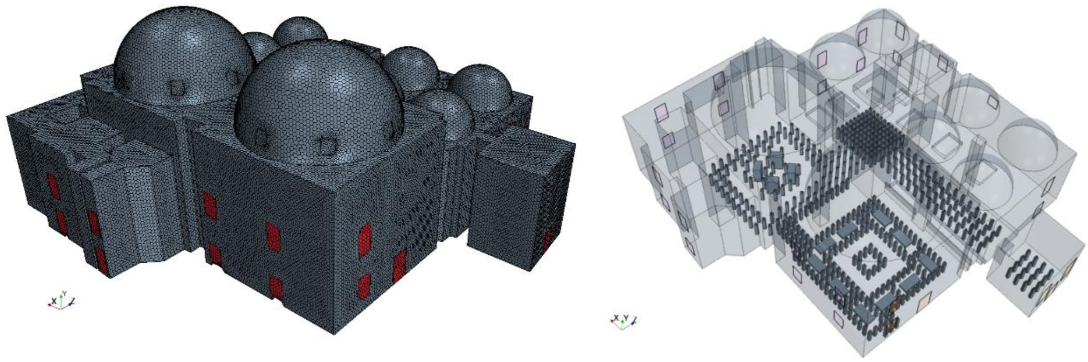


Figure 3. Simplified CAD Model after re-meshing showing the different windows

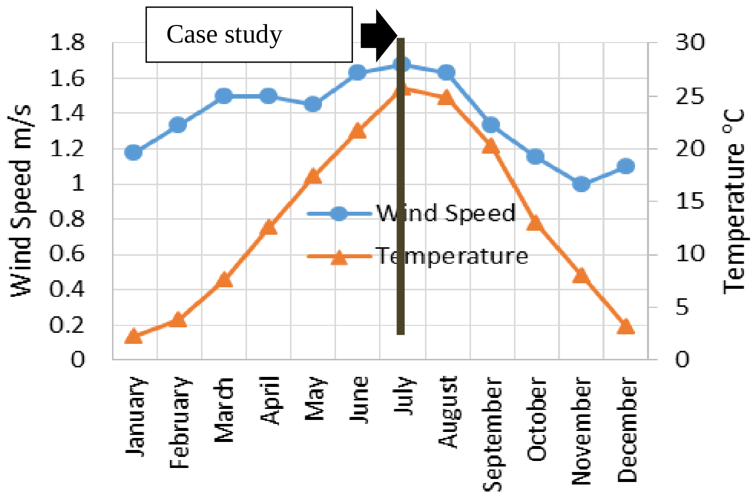


Figure 4. Average wind speed magnitude and temperature over last 4 years at 10 meters from ground

Results and Discussions

Flow Distribution in the horizontal planes

During summer all the available windows are assumed open. The air velocity and temperature have been set according to the Turkish State Meteorological information, which re-presented in Figure 4. The velocity vectors on a plane located 1.6 m above the floor is shown in Figure 5. The figure shows that the air is mostly entering the museum from the north side windows while all other windows are acting as air exits. The worst area that has almost stagnation air is the most crowded area near the tomb of Mevlana. This is attributed to the absence of any windows in the south side. The two windows on the east helps to circulate the air around the tombs but with relatively lower velocities. At the entrance door interestingly the visitor will feel air draft from inside which in summer will definitely be cooler than outside. Some areas, particularly corners have low air motion and therefore it is expected to have emission contaminations and also higher temperature. Different vortices can be observed which can lead to contamination, at their centres however by nature vortices are always associated with oscillations which may limits the contaminations. The high draft from the north side is clearly shown at the open windows. Low velocity regions in general are located in the corners and in the wakes behind any obstacles. Clearly, the south side of the museum has the lowest air velocity during this month.

Flow Distribution in the vertical planes

Figure 6 shows the velocity vector distribution in three different vertical planes located. The domes have significant effect in enhancing the air motion and circulation. as shown in all the three section. Section (c) is taken from the centre of the entrance door and passing by the most crowded place near the tombs. Although the velocity is low in near the floor, there is a high circulation at the upper part due to the dome shape effect and the east windows. At the entrance section there is a jet of air which acts as a tunnel which lead to shear flow and therefore causing recirculation zone at the upper part. It is worth mentioning that there are small windows located on the domes and it is believed these windows could have great influence on the flow distribution as they will enhance the chimney effect and the natural ventilation particularly if the temperature outside is hotter than inside. In this study these windows were assumed closed.

Figure 7 shows the temperature inside the museum can reach 31 ^{o}C in limited locations particularly where there is airflow velocity is low. The area where visitors gathered is the most affected area. Having lower air jet or mechanical fans may increase the air flow velocity around the visitors. It is worth mentioning that the museum walls have been assumed adiabatic as no data was available to have accurate value of their temperature. In fact it is expected that in summer the walls will have low temperature and therefore there should be some heat absorbed by the walls and therefore helps in reducing the temperature. It is also important to highlight the importance of opening the windows in the dome as the high temperature air can rise and exits.

Further work to be considered

- Validate the model by having experimental measurements
- Contaminations of emitted gases
- Combinations of open windows to have better air distribution
- Locating dead zones and providing mechanical fans
- Studying the transient case such as the first one hour early morning or the effect of opening windows for specific period of time
- Simulating the air flow and gas concentrations at different times
- Identify the humidity distribution

Achieving such calculations need further data to simulate the spatial distribution of flow velocity, temperature, gas concentrations and humidity. Some of these data are the followings:

- Temperature of the walls and wall specifications
- Wind speed at the different locations outside and close to the museum

- Measurements of air velocities and gas concentrations inside the museum for validating the model.
- Meteorological hourly based data
- Visitors number on a monthly based to be able to identify the worst conditions

Different methods can be suggested to improve air ventilation

- In order to fully utilize thermal buoyancy, air openings at a lower end (mostly 500 mm above the indoor floor) can be considered. Air openings need to be installed at dominant wind direction of summer, and avoid the dominant wind direction of winter

Windows located on the doom should be automatically opened from time to time to help naturally ventilating the museum.

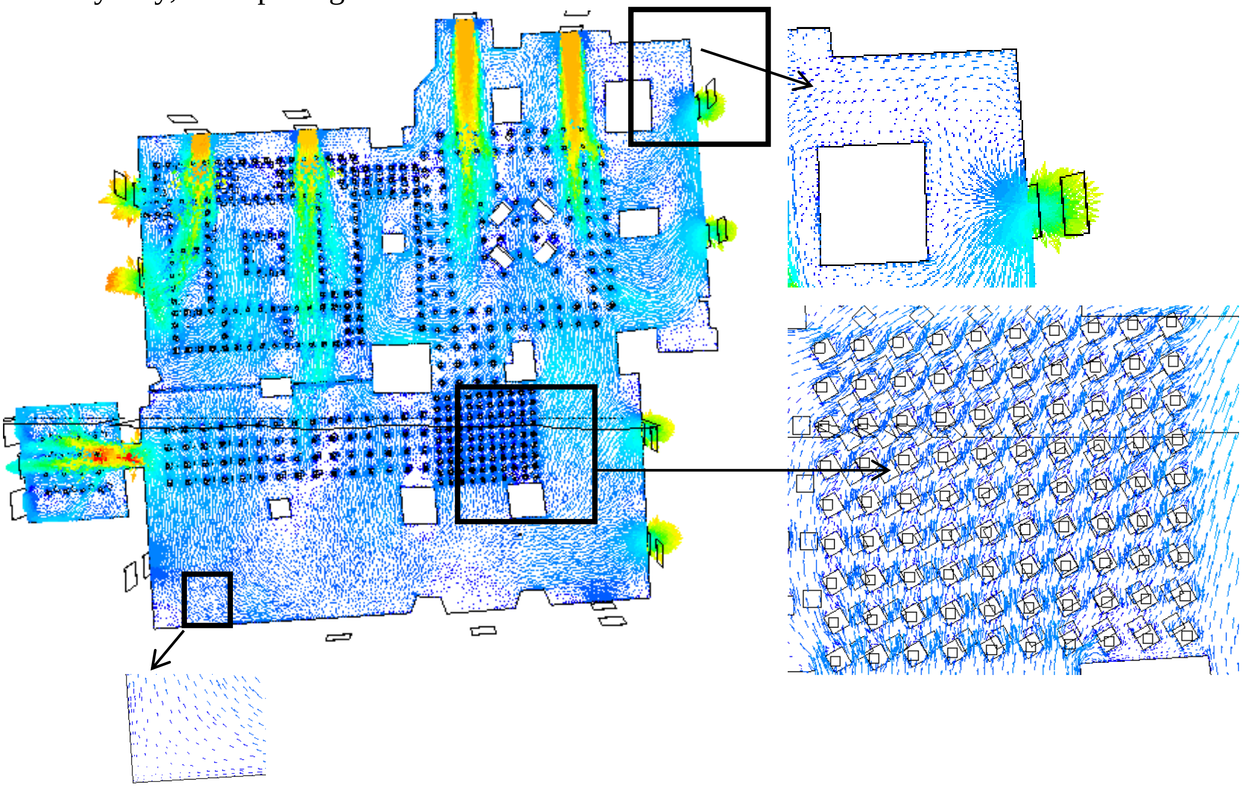
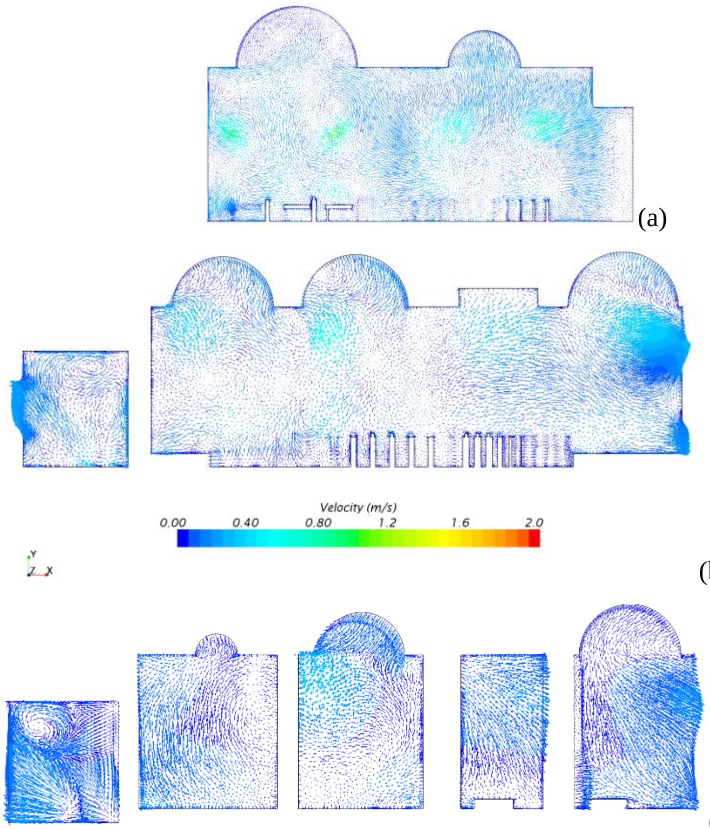


Figure 5: Air velocity vector distribution on a horizontal plane located at 1.6 m from the floor



(a)

(b)

(c)

Figure 6. Velocity vector distribution in different vertical planes

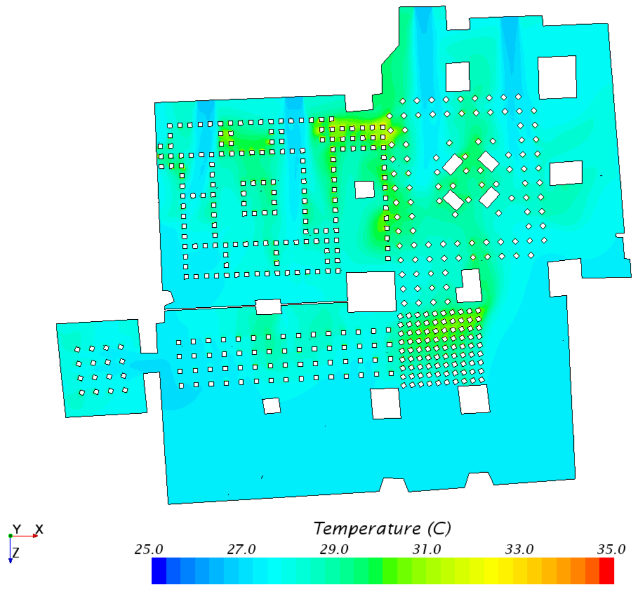


Figure 7: Temperature distribution throughout a horizontal plane located 1.6 m above the floor

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Conclusions

This limited and preliminary study has demonstrated that a CFD based analysis of the ventilation and air distribution is, in principle, viable. Analysis of air distribution and emission contamination during a specific month and obtaining optimum design would necessitate the use of realistic, detailed, geometry and further data and some experimental work. However, this is just a matter of data collection and computing resource.

Some general observations can be drawn from this work which was carried out during the month of July. Given the simplification of the geometry they are best understood as preliminary hypotheses, which require further investigation.

- Generally, the most area that has lower air velocity is the location of the tombs, where most of the people gathered.
- The east side windows has great effect of improving air circulations
- High temperature is always located where people are gathered and natural ventilation can actually improve by opening the top windows and have a chimney effect.
- Some areas particularly the corners are almost stagnant and can lead to emission contaminations.
- Airflow velocity was generally low and beyond the comfortable range in many locations inside the museum.

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