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Numerical Investigations of Indoor Air Quality inside Al-Haram Mosque in Makkah

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Abstract

The air conditioning applications in mosques are considered as one of the important HVAC applications, which indoor air quality depend on the behavior of the airflow, the distributions of temperatures and relative humidity and concentration of carbon dioxide due to high occupancy load of people. The paper is devoted to numerically investigate the influence of ventilation rate on indoor air quality. The example shown here is Al-Masa'a between Al-Safa and Al-Marwa hills inside Al-Haram mosque located at Makkah-Saudi Arabia. The work focuses on air flow, thermal behavior and carbon dioxide dispersion where large number of people. Five different cases for change in ACH are studied to reveal the impact of changing it on the all people. The performance of the air conditioning system is characterized by airflow patterns, temperature, relative humidity contours and CO2 concentration as well as the most commonly used comfort parameters PMV and PPD based on Fanger's model. The study is carried out using computational fluid dynamics (CFD) simulation techniques as embedded in the commercially available CFD code (ANSYS 15). The CFD modeling techniques solved the continuity, momentum and energy conservation equations in addition to RNG $k - \varepsilon$ model equations for turbulence closure. Mesh sizes used in present work exceeded 4.5 million approximately.

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Keywords: Heat transfer; CFD, Air Flow Regimes, Mosques, Thermal Comfort

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1. Introduction

Mosques are characterized by having a unique operation schedule as compared to other types of buildings. They are usually occupied five intermittent times a day all year round, with an average occupancy period ranging from 45 to 60 min. People do not usually come to the mosque at a specific time during this hour but rather gradually and maximum occupancy is expected to occur during the actual performance of prayer which lasts for about 15–20 min. Once the prayer is over, people will gradually leave the mosque. The quality of indoor air inside mosques and large buildings is important not only for occupants comfort but also for their health. Poor indoor air quality (IAQ) has been tied to symptoms like headaches, fatigue, trouble concentrating, and irritation of the eyes, nose, throat and lungs. Also, some specific diseases have been linked to specific air contaminants or indoor environments, like asthma with damp indoor environments [1-11]. The purpose of this paper focuses on airflow patterns, thermal behaviors and carbon dioxide dispersion in air-conditioned Mosques. That is in order to improve the quality of the indoor air. A large size of air conditioned Mosque was selected and it is located in Makkah-Saudi Arabia.

2. Mathematical Modelling

Governing Equations

Air motion in 3D configurations is treated as an incompressible fluid flow governed by continuity equation which is described in vector form as follows:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \mathbf{V}) = 0$$

Other main governing equations are three momentum components (Navier stokes equations), energy, and species concentrations which are described as follows:

$$x-momentum \quad \frac{\partial(\rho u)}{\partial t} + div(\rho u \mathbf{u}) = -\frac{\partial p}{\partial x} + div(\mu\, grad u) + S_{Mx}$$

$$y-momentum \quad \frac{\partial(\rho v)}{\partial t} + div(\rho v \mathbf{u}) = -\frac{\partial p}{\partial y} + div(\mu\, grad v) + S_{My}$$

$$z-momentum \quad \frac{\partial(\rho w)}{\partial t} + div(\rho w \mathbf{u}) = -\frac{\partial p}{\partial z} + div(\mu\, grad w) + S_{Mz}$$

$$energy \quad \frac{\partial(\rho i)}{\partial t} + div(\rho i \mathbf{u}) = -p\, div\, \mathbf{u} + div(k\, grad T) + \Phi + S_i$$

$$species \quad \frac{\partial(\rho\phi)}{\partial t} + div(\rho\phi\, \mathbf{u}) = div(\Gamma\, grad\, \phi) + S_\phi$$

Thermal Comfort Factors

Thermal comfort Factors were described in ASHRAE Standard, [1] and ISO 7730, [1]. The most important parameters of global comfort were considered to be Fanger, as reported in [1]:

- Predicted Mean Vote (PMV)
- Predicted Percentage Dissatisfied (PPD %)

PMV is calculated from the formula:

$$PMV = [0{,}352 \cdot e(-0{,}036 \cdot M)] + 0{,}028] \cdot \left\{ \begin{array}{l} (M-W) - 3{,}05 \cdot 10^{-3} \cdot [5733 - 6{,}99 \cdot (M-W) - Pa] \\ -0{,}42[(M-W) - 58.15] - 1{,}7 \cdot 10^{-5} \cdot M \cdot (5867 - Pa) \\ -0{,}0014 \cdot M \cdot (34 - t_a) - 3.96 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 \\ -(t_{mrt} + 273)^4] - f_{cl} \cdot h_{cl} \cdot (t_{cl} - t_a) \end{array} \right\}$$

The Predicted Percentage Dissatisfied expresses the heat sensations of a group of people dissatisfied with the thermal conditions in a given space. It is calculated from the formula:

$$PPD = 100 - 95 \cdot e(-0{,}03353 \cdot PMV^4 - 0{,}2179 \cdot PMV^2)$$

3. Assessment and Validation

The validation presented here was based on prediction of the work of Zhang and Chen [11]. They used the computational fluid dynamics (CFD) and measurement technique to simulate and analyse the indoor airflow field in a room. The present validation used Fluent 15 code for the Zhang and Chen [11] work. The mixed convection simulation is based on the experiments conducted by Blay et al. [5]. They measured the air temperature, velocity and the energy turbulent distributions. The experiments were conducted in a room with geometry of H= 1.04 m, L= 1.04 m, and D= 0.7 m. In order to compare the accuracy of results of these turbulence models, vertical line in the centre was selected to show distribution of velocity along it as shown in figure 1. It can be concluded that Standard k-Є Model results are far from experimental results because it isn't suited for low turbulence regions. The RNG k-Є Model results seem to be closer to the experimental results which better represent the air flow regimes. So, in this study, the RNG k-Є Model was selected, other models are still options to be used. Figure 2 shows the comparisons between predicted and experimentally measured velocity distributions. Good agreement is denoted between velocity deduced using the CFD (Fluent 15) and those of the work of Zhang and Chen [11]. This confirms the ability of FLUENT 15 to predict the air flow patterns inside the mosques or other large spaces accurately.

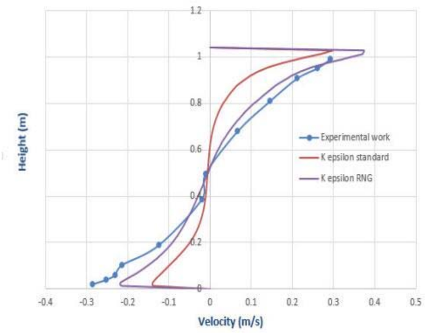

Fig 1. Comparison between two different turbulence models and measured air velocity.

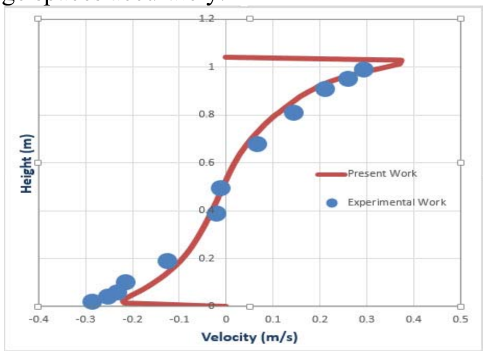

Fig 2. Comparison between measured and calculated velocity profiles.

Model Description

The part from first floor of Al-Masa'aa configuration in Al-Haram mosque (the area between every four columns that represent the whole Masa'aa) with 5.5m ×20m × 7.7 m (5.5m in length (L), 20 m in width (W), and 7.7 m in height (H)) All data are taken from an actual data on AutoCAD software. The mesh is generated using ANSYS 15 program with tetrahedral elements. The mesh independency test is making. The aim of it is to test the solution using different mesh intervals until the solution converges. The domain assembly case was finally discretized into 4,500,000 averaged tetrahedral elements Based on mesh statistics as shown in figure 3. The indoor initial and boundary conditions are simply assumed as shown in table 1 according to moderate summer outdoor conditions of Makkah-Saudi Arabia, which significantly was recorded in the month of August.

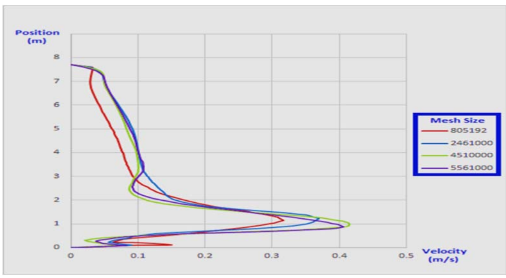

Fig 3. Comparing velocity magnitude at a vertical line at (X = 0, Y = 2 m) using different mesh sizes (case 6).

Table 1. summary of boundary conditions

Boundary	Value
Ceiling temperature	[24°C]
Walls temperature	[30,35°C]
Floor temperature	[24°C]
Outlet air temperature	[12°C]
ACH	10
Lights	200 [W/m^2],

Tables 2 and 3 display the standard PMV classifications and assumptions

Table 2: Range of PMV and PPD

PMV	Thermal Sensation	PPD(%)
+3	Hot	**100**
+2	Warm	**75**
+1	Slightly Warm	**25**
0	Neutral	**5**
-1	Slightly Cool	**25**
-2	Cool	**75**
-3	Cold	**100**

Table 3: Occupants boundary details

Occupant Data	value
Gender	Male
Activity type	walking
Metabolic rate	2 [met].
Skin temperature	32.5 [C]
breathing rate	8 L/min
Species mass fraction from mouth	0.042 $kg_w / kg_{d.a}$
CO2 concentration in the human respiration	0.036 L_{co2}/L_a

4. Cases and Results

The effect of ventilation rate (ACH) on the indoor air quality inside mosque is investigated for the ACH (6, 8, 10, 12 and 14) as shown in case 1 to case 5 below with 150 persons standing in parallel rows. All results represented here at horizontal planes at Z=1.6m above finished floor.

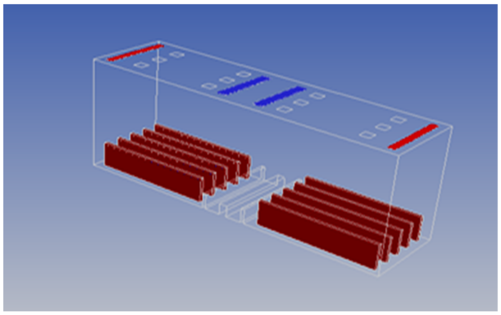

Fig 4. The domain of case study configuration Modeled by ANSYS 15.

Case1:

In this case, the value of air change per hour inside the mosque is assumed as ACH = 6.

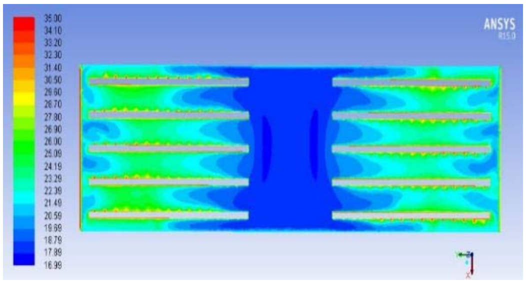

Figure 5. Temperature contours (°C),

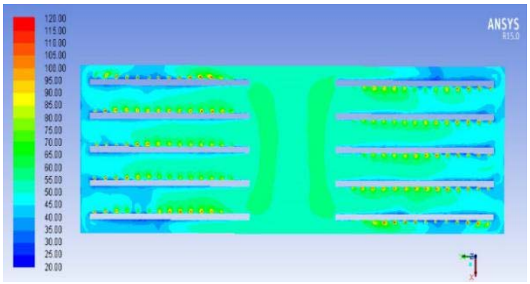

Figure 6. Relative humidity contours %),

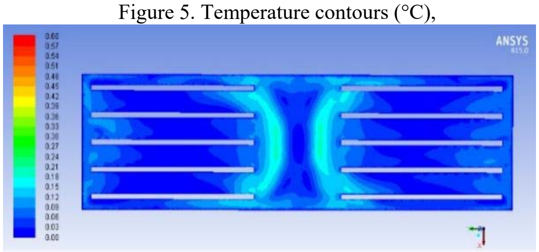

Figure 7. Velocity magnitude contours (m/s),

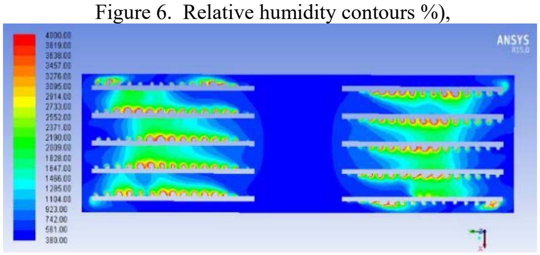

Figure 8. CO2 contours (°C),

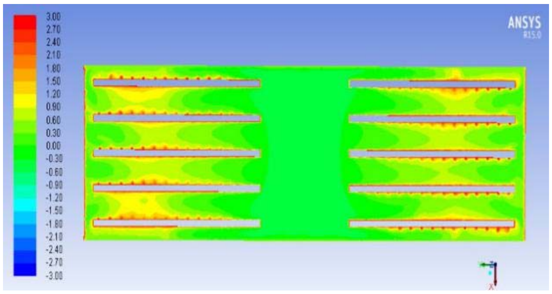

Figure 9. PMV contours,

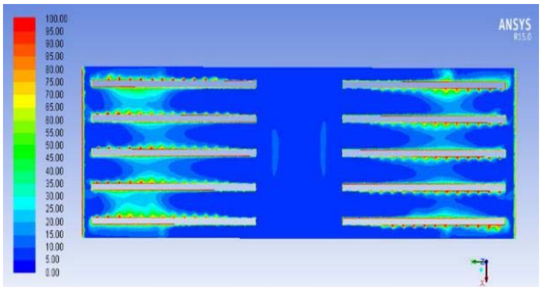

Figure 10. PPD contours,

Case 2:

In this case the value of air change per hour inside the mosque is assumed to be 8, the corresponding predictions are shown in Figures 11-16 that includes temperature, relative humidity, velocities, CO2 concentrations, also PMV and PPD contours at a horizontal plane at Z of 1.6 m.

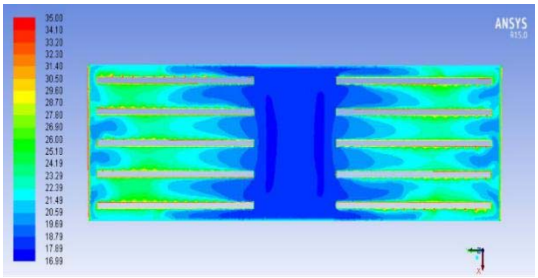

Figure 11. Temperature contours (°C), horizontal Plane at Z= 1.6m.

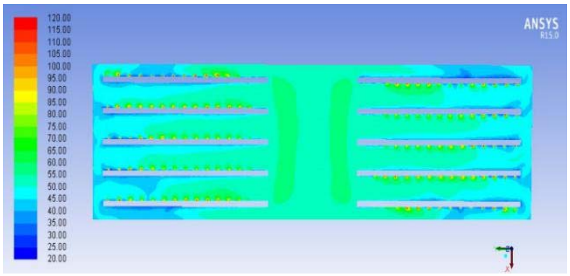

Figure 12. Relative humidity contours (%), horizontal Plane at Z= 1.6m.

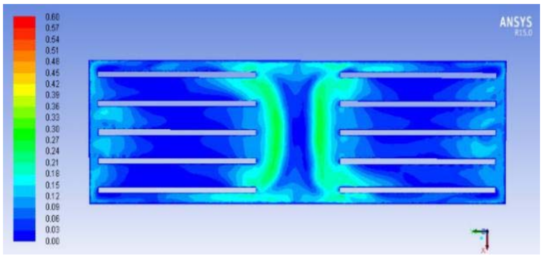

Figure 13. Velocity magnitude contours (m/s),

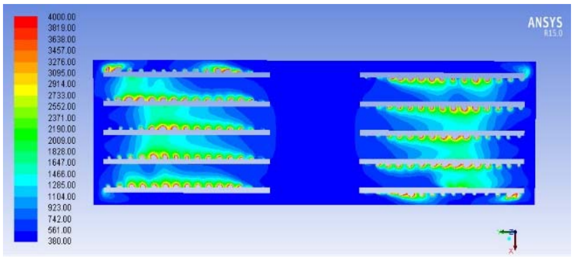

Figure 14. CO2 contours (°C),

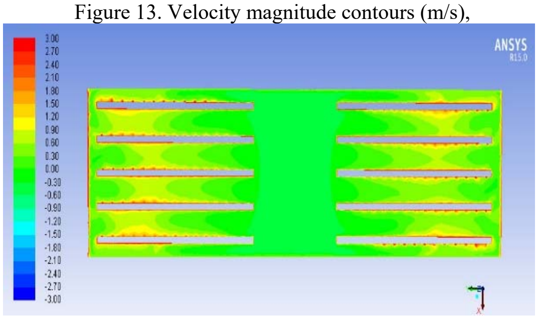

Figure 15. PMV contours

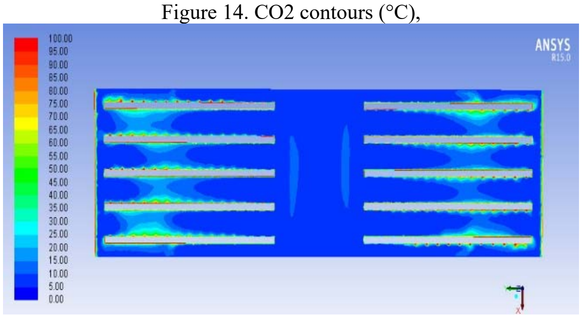

Figure 16. PPD contours,

Case 3:

The air change per hour was increased to 10 according to ASHREA [1,2] and the corresponding predicted contours of temperature, relative humidity,velocities,CO2 concentrations, also PMV and PPD contours at a horizontal plane at Z of 1.6 m. are shown in Figures 17 to 22 below.

Case 4:

This case describes the airflow characteristics when the air change per hour is 12 according to ASHREA ;the corresponding predictions of temperature, relative humidity,velocities,CO2 concentrations, also PMV and PPD contours at a horizontal plane at Z of 1.6 m. are shown in Figures 23-28 below.

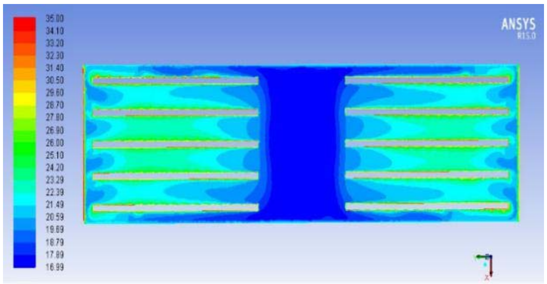

Figure 17. Temperature contours (°C),

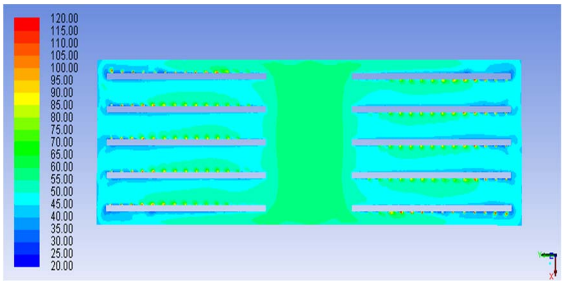

Figure 18. Relative humidity contours (%),

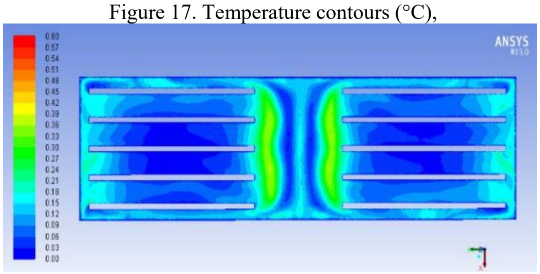

Figure 19.Velocity magnitude contours (m/s),

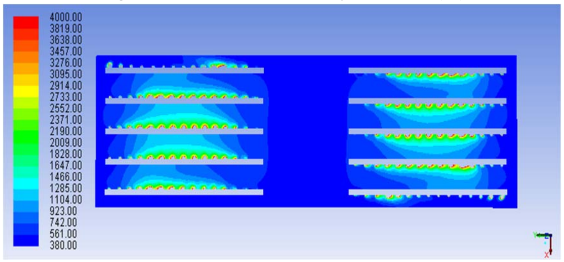

Figure 20. CO2 contours (PPM)

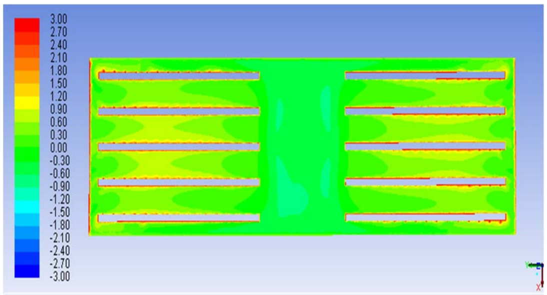

Figure 21. PMV contours,

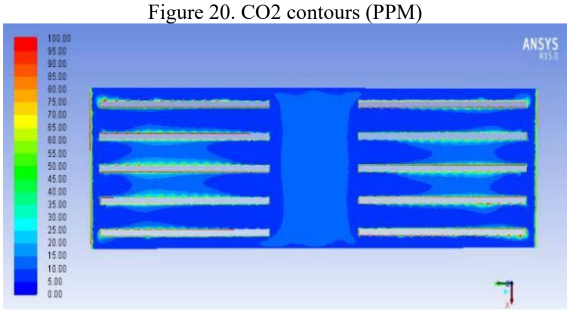

Figure 22. PPD contours,

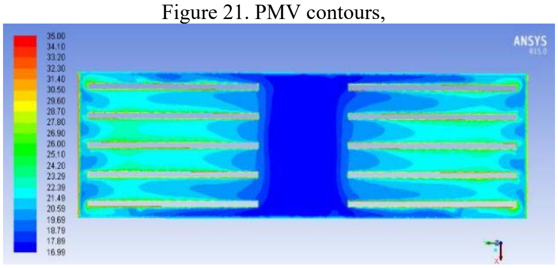

Figure 23. Temperature contours (°C),

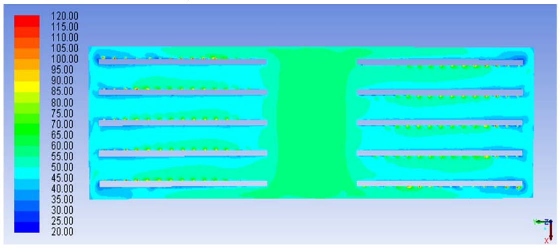

Figure 24. Relative humidity contours (%),

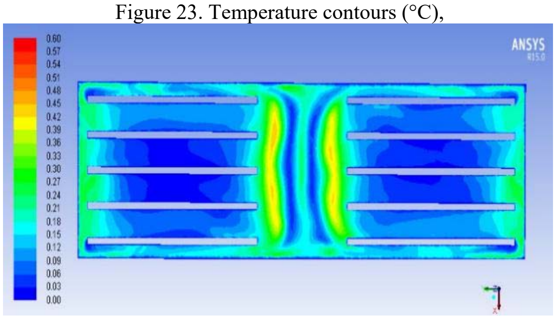

Figure 25. Velocity magnitude contours (m/s),

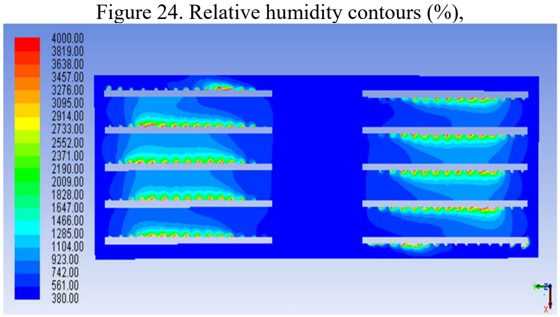

Figure 26. CO2 contours (PPM)

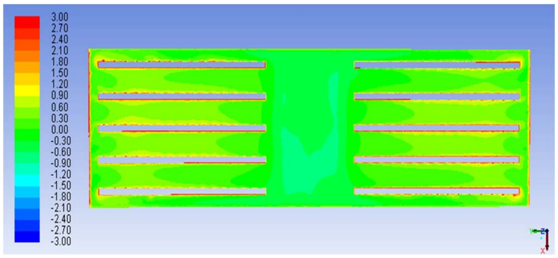

Figure 27.PMV contours,

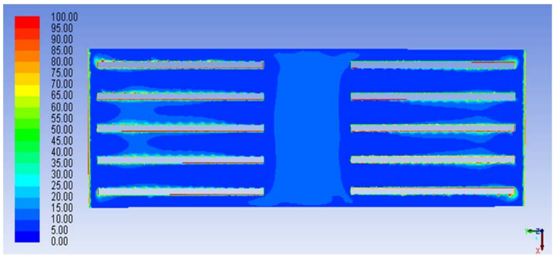

Figure 28. PPD contours,

Case 5:

This case also describes the airflow characteristics when ACH is 14, these include predictions of temperature, relative humidity, velocities, CO2 concentrations, also PMV and PPD contours at a horizontal plane at Z of 1.6 m. as shown in Figures 29-34.

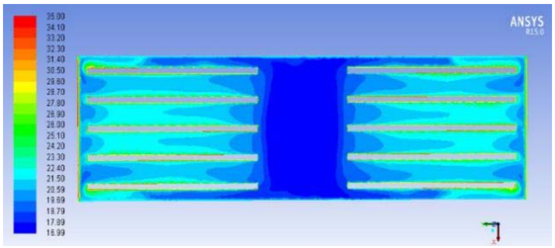

Figure 29. Temperature contours (°C),

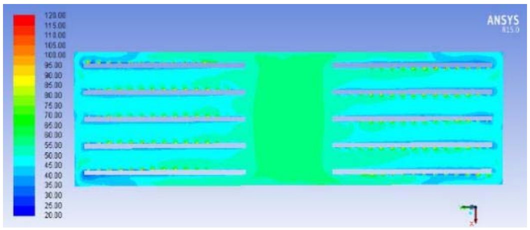

Figure 30. Relative humidity contours (%),

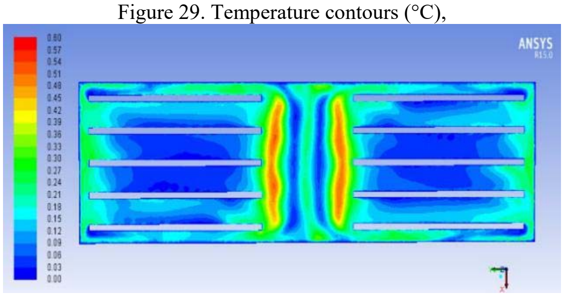

Figure 31. Velocity magnitude contours (m/s),

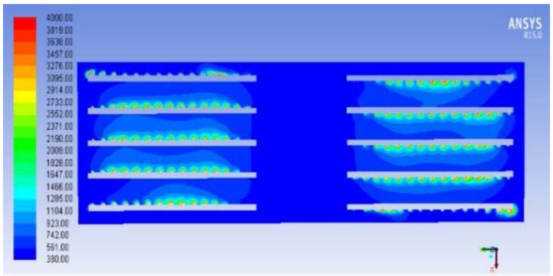

Figure 32. CO2 contours (PPM)

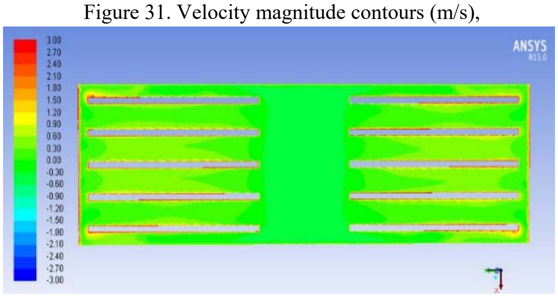

Figure 33.PMV contours,

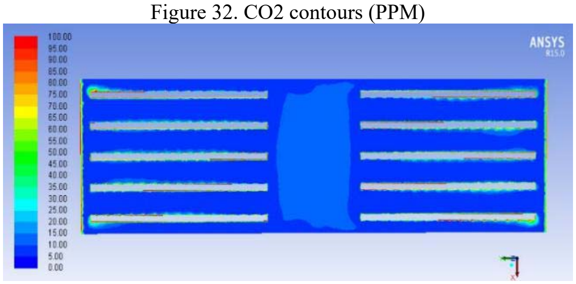

Figure 34. PPD contours,

A summary of the obtained results for the various cases is shown in tabulated form in Table 4 for a horizontal plane at Z=1.6 m.

Table 4 summary show the discussion of results for previous five cases

No.	CO2	PMV	PPD
Case 1	carbon dioxide around 1200 ppm	The average of PMV is 1 approximately	PPD reach to 25%
Case2	carbon dioxide around 1000 ppm	PMV average is 0.8 approximately	PPD reach to 18%
Case3	carbon dioxide around 700 ppm	PMV average is 0.4 approximately	PPD reach to 12%
Case4	carbon dioxide around 600 ppm	The average of PMV is 0.3 approximately	PPD reach to 10%
Case5	carbon dioxide around 500 ppm	PMV average -0.2 approximately	PPD reach to 7%

.

5. Conclusions

1. According to Fanger's model case one was slightly warm because the temperature is high and according to ASHREA the concentration of CO2 is also high and it's greater than 1000 ppm so this design is rejected. While case two had good PMV and PPD but the concentration of CO2 is bad inside the mosque.
2. In Case 3, 4 and 5, all the three cases are accepted because it reach to neutral case depend on PMV, PPD and about the CO2 concentration is less than 1000 ppm depend on ASHREA.
3. case three when the ACH 10 is the best case among the others cases because that led to minimize the energy consumption with good temperature and good air quality inside the mosque
4. As the ventilation rate (ACH), increase the contaminant concentration (CO2) decrease and velocity increase because the velocity depend mainly on the ACH value and are directly proportional to it.
5. Generally, predicting thermal sensations by means of modelling and CFD software may be more practical for HVAC engineers but still not totally reliable.

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