Investigation of Airflow Characteristics and Thermal Comfort in Indoor Squash Court

Mahmoud G. Abd Elfatah [1*], Mahmoud A. Fouad[2], Taher Halawa[3], Mohamed Aly[1]

[1] Department of Mechatronics Engineering, Faculty of Engineering, October 6 University, 6th of October City,12585, Giza, Egypt.
* Email of Corresponding Author: omarahmed.eng@o6u.edu.eg

[2] Mechanical Power Engineering Department, Faculty of Engineering, Cairo University, Giza 12613, Egypt.

[3] The British University in Egypt (BUE), El-Sherouk City, Cairo, 11837, Egypt.

Abstract –This study focuses on designing an air conditioning system that can provide the required thermal conditions in an indoor squash court. That will be followed by the World Squash Federation (WSF) and the Specialized College for Sports Medicine in America (ACSM), which suggested keeping the temperature of the air inside every facility used for intense activity to be at the range of 20-22 C, with relative humidity levels lower than 60%. The World Squash Federation recommended the air temperature range between 15-25 °C, with the ideal range of 18-20 °C with relative humidity levels lower than 60%, considering maintaining ball surface heat at 40-45 °C or above. Suppose the ball's temperature decreases below that range. In that case, the ball's rebound will be decreased, which will be done by investigating temperature and velocity distribution, relative humidity, $co2$ level, and the effect of changing the inlet velocity for each air conditioning system design. The difference between each air conditioning system will be in the location and number of supply and extract openings. The study was carried out using CFD simulation by ANSYS FLUENT 17.2. The CFD modeling techniques will solve the continuity, momentum, and energy equations, allowing better and more meaningful predictions of the flow patterns by using the realizable k-ε as a turbulence model and its function of enhanced wall treatment.

Keywords: Indoor Squash Hall, sports buildings, Computational fluid dynamics (CFD), Ventilation, thermal and humidity conditions, Thermal comfort

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1 Introduction

Squash is one of the highest activity-level games. That made the game require a lot of thermal conditions to assure the comfort and safety of the players and spectators inside the court. The required thermal conditions have been determined by the Specialized College for Sports Medicine in America(ACSM) (ACSM 2011) and the World Squash Federation (WSF) (WSF 2010). Thermal comfort can be defined as "that condition of mind which expresses satisfaction with the thermal environment" (ISO7730 2005)

Thermal comfort is not just pleasing conditions. It is more than that; it is part of a crucial survival behavior. Whenever humans feel too warm or too cold, a warning system is notified by our basic instincts. The human body is a very efficient piece of machinery and can keep up core temperature within a very narrow range of 37°C. Some actions are subconscious, like diverting blood from spread areas like hands and feet. That helped keep the vital organs heat in cold environments or begin sweating in heat environments. Acutely aware actions embrace removing or adding clothes and adapting our activity level. However, whichever approach has been checked on, the proper thermal conditions are required to survive (Baker 2009). If the thermal environment does not meet expectations, occupants of a building will try to influence the thermal environment to make it do so by installing local electric heating or cooling units, equipment (the air conditioner)

1.1 Thermal comfort for squash court

The squash players perform at a high activity level inside the court; recommended comfort zones from standard organizations such as ASHRAE 55 (ASHRAE 2010) and ISO 7730 (ISO7730 2005) mainly apply to low-level activity in offices. Furthermore, the presented work will depend on the recommendation of another organization, the American College of Sports Medicine (ACSM 2010), which recommends maintaining air temperature in all physical activity spaces between 20-22 °C, with relative humidity levels lower than 60%. The World Squash Federation(WSF 2010) recommends the range of air temperature between 15-25 °C and the ideal range of 18-23 °C with relative humidity levels lower than 60%. The recommended thermal conditions for both of them are almost the same. The International Fitness Association (IFA 2017) recommends high activity levels such as weight training, cardio, tennis, and squash at an 18-20 °C air temperature. The ACSM and IFA temperatures are far lower than the summer comfort temperatures recommended in the ASHRAE and ISO office standards.

1.2 Squash court specification

There are many specifications that the Squash Federation has recommended for the squash court. The design of the court for each type, the materials used for the walls and floor of the squash court, and lighting intensity. Ventilation parameters and their range all of that will be discussed in detail.

1.2.1 Dimension of Squash Courts:

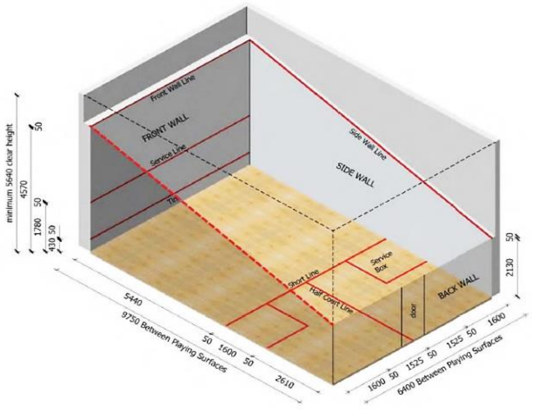


Figure 1: Sizes of singles squash court (WSF 2010)

The essential dimension:

- The length of the court is 9750 mm.
- The width of the court is 6400 mm.
- Tin height 480 mm
- The minimum height of the court is 5640 mm

1.2.2 Lighting Inside Squash Court

The light used inside the court must be artificial. The intensity of illumination inside the court will be acceptable.

- The minimum standard is 300 lux, nearly equal to 2.37 w/m$^{2.}$
- The recommended standard is 500 lux, nearly equal to 4 w/m$^{2.}$
- The recommended standard for LED is 600 lux, nearly equal to 4.782 w/m$^{2.}$

In the case of using LED for the court lighting, it is recommended to use 6 LEDs as a minimum in a single court and 8 LEDs for a double court.

The previous values have recommended standard lighting to ensure no shadow inside the court.

1.2.3 Heating and Ventilation for The Court

1.2.3.1 Temperature and Relative Humidity:

The Squash Federation recommended that all zones for the audience, referee, and players be air-conditioned with a system that can reach temperatures between 15-25 ℃ and an ideal range of 18-20 ℃. The relative humidity must be less than 60% inside the court.

1.2.3.2 Location of Grilles and Other Equipment

The only parts that can be used as a location for the supply and outlet grills are below the above of the tin by 50 mm and in the ceiling above 5000 mm without a shadow on the front wall.

2 Previous Research

(Yongchao Zhai 2015) This research investigated thermal comfort and air movement at elevated activity levels. Comfort votes were obtained from 20 subjects pedaling a bicycle ergometer at 2, 4, and 6 MET exercise intensities in four temperatures (20, 22, 24, 26 °C, RH 50%) under personally controlled ceiling fan airflow, as well as in a 20 °C still-air reference condition. An additional test of frontal airflow was conducted at 26 °C.

The hypothesis that air movement and higher temperatures would produce equal or better comfort and perceived air quality below the reference condition was confirmed for every temperature up to 26 °C. Subjects preferred air speeds up to 2.3 m/s to maintain an acceptable thermal environment at 6 MET.

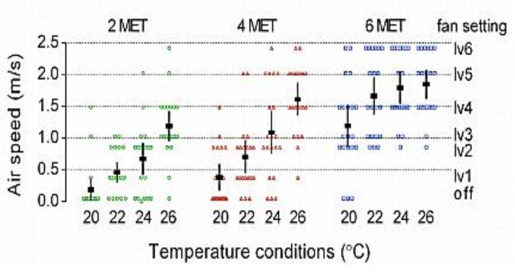


Figure 2: Preferred air speed at each test condition (Yongchao Zhai 2015)

Fig. 2-1 shows the preferred air speeds at each temperature condition. Both temperature and MET significantly affect the preferred air speeds ($p<0.05$). At 2 MET, subjects preferred very little air movement at 20 °C (0.19 m/s) and 22 °C (0.46 m/s). Preferred air speeds increased to 0.67 m/s at 24 °C and 1.19 m/s at 26 °C. At 4 MET, the preferred air speeds were 0.38 and 0.70 m/s at 20 °C and 22 °C, increasing to 1.09 and 1.61 m/s for 24 °C and 26 °C, respectively. At 6 MET, the preferred air movement was quite high at all temperatures: at 20°C, the mean air speed was 1.19 m/s, and at 22, 24, and 26 °C, it was 1.66, 1.79, and 1.85 m/s, respectively.

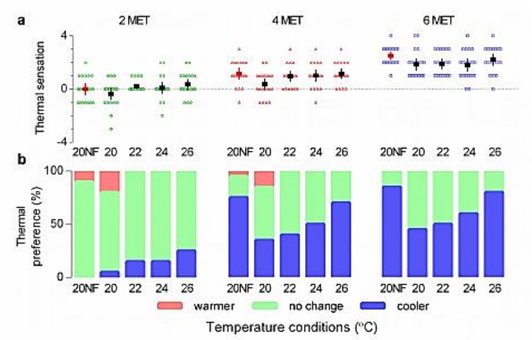
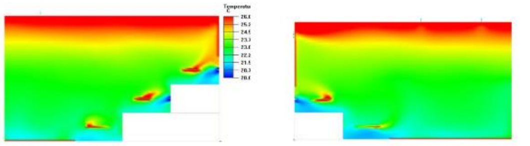


Figure 3: Thermal requirements gathered from players in different cases (Yongchao Zhai 2015)

(AI.Stamou 2008) A Computational Fluid Dynamics (CFD) model was used to evaluate the thermal comfort conditions in the Galati Arena's indoor stadium, which hosted rhythmic gymnastics and table tennis during the Olympic Games "Athens 2004". The CFD code CFX was applied to calculate the 3-D airflow and temperature fields in the Arena for various values of temperatures (Tin) of conditioned inlet air. Calculated mean velocities and temperatures were used to determine the thermal comfort indices PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) and to evaluate the thermal conditions in the various regions of the Arena. Calculated PMV and PPD values showed that thermal conditions in the Galati Arena

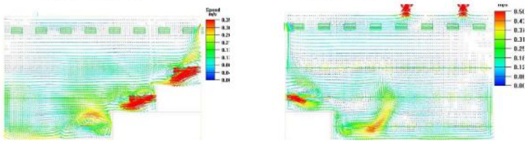
(X. Ma 2002) in this research, numerical and experimental methods were utilized to recreate and investigate the indoor airflow field in the isothermal-cooled space of an exercise room. Numerical strategies re-enacted some unique airflow patterns indicated by various supply air. The creators set up the full-scale trial investigation of the airflow patterns example of a similar gymnasium. Estimation information and investigation of air appropriation were displayed in which the airflow is isothermal.

(Wu, Xuehui 2006) this research tries to evaluate the use of displacement ventilation (DV) system in large spaces such as gymnasiums and divides the large space into two zones competition zone and an audience zone; the results show that the(DV) system can meet the necessity of wind current of rivalry lobby. The circulations of temperature and speed are homogeneous in the gymnasium, and their value is acceptable.



(a) Distribution of temperature on plan which X=26m

(b) Distribution of temperature on plan which X=30m



(c) Distribution of velocity on plan which X=26m

(d) Distribution of velocity on plan which X=30m

Figure 4: Distribution of temperature and velocity on some plans. (Wu, Xuehui 2006)

(X. Sui 2014) this research used a ball spout as an air inlet supply. The author considers adjusting the spout angle to avoid the upturning hot jet because its supply is hot air. The author used CFD software to investigate the flow pattern and temperature distribution to reach thermal comfort for the court; two cases have been studied with horizontal angles and 30 angles, and the result showed that releasing air on a horizontal plane can meet the outline prerequisites. That is because the supply air temperature distinction is generally small, and hot air drifting has little impact on air conveyance.

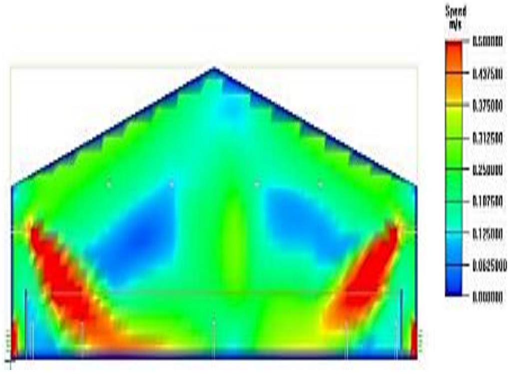


Figure 5: Velocity field at x=8.3m with 30 angles (X. Sui 2014)

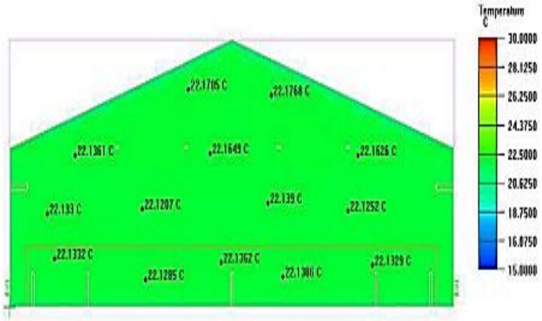


Figure 6: Temperature distribution at x=8.3m with horizontal angle (X. Sui 2014)

(Dana E SACKS 2007) this research is constrained to the impacts of deficient ventilation on people. The authors surveyed the IEQ of a retrofitted private exercise center in Focal, New Jersey, amid long stretches of activity after regular cooling season workdays in July-September 2013. Air tests were taken for four hours (16:00-20:00) once every week for seven weeks. Medium-term estimations were directed on about fourteen days to appraise ventilation rates. Temperature (T), relative humidity (RH%), and carbon dioxide fixations (CO2) in parts per million (ppm) as a marker of air trade or ventilation rate were recorded. We reliably discovered high CO2. At the point when instruments were left medium-term, CO2 gradually declined. Information for T and RH% stayed reliable. The warming, ventilation, and cooling framework did not adequately ventilate the gymnasium for physical wellness/movement.

The research recommends depending only on air conditioning systems that keep and monitor the temperature without considering the hazard of CO2 level, especially in spaces with high activity levels, and use fans to recirculate the air and dilute the CO2 concentration.

3 Methods

CFD is a powerful tool for the analysis of fluid flows. It is a computer-based simulation technique providing an approximate two- or three-dimensional solution to fluid motion equations. The technique is characterized by a division of the region in which flow is to be computed the computational domain, into a huge number of much smaller domains referred to as mesh or grid cells. Complex geometries and time-dependent flows are readily handled. The solution consists of values of flow parameters of interest, such as velocity or gas concentration, calculated at each grid cell. It provides a complete time-dependent picture of complex fluid flows.

For the present study, CFD simulation for airflow inside the squash court, numerical techniques were used to model the airflow characteristics. The governing equations in this model are Continuity, Momentum, and Energy.

- Continuity equation with three-dimensional:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \quad \textbf{(1)}$$

- Three momentum equations in Cartesian x, y, and z coordinates:

$$\rho\frac{Du}{Dt}=\rho g_x-\frac{\partial P}{\partial x}+\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{yx}}{\partial y}+\frac{\partial \tau_{zx}}{\partial z} \quad (2)$$

$$\rho\frac{Dv}{Dt}=\rho g_y-\frac{\partial P}{\partial y}+\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial \tau_{yy}}{\partial y}+\frac{\partial \tau_{zy}}{\partial z} \quad (3)$$

$$\rho\frac{Dw}{Dt}=\rho g_z-\frac{\partial P}{\partial z}+\frac{\partial \tau_{xz}}{\partial x}+\frac{\partial \tau_{yz}}{\partial y}+\frac{\partial \tau_{zz}}{\partial z} \quad (4)$$

- Conservation equation for species Yi:

$$\frac{\partial y}{\partial t}(\rho Y_i)+\nabla\cdot(\rho\vec{v}Y_i)=-\nabla\cdot\vec{J}_i+R_i. \quad (5)$$

- Energy equation:

$$\rho\frac{\partial h}{\partial t}+\rho u\frac{\partial h}{\partial x}+\rho v\frac{\partial h}{\partial y}+\rho w\frac{\partial h}{\partial z}=\frac{\partial}{\partial x}\left[k\frac{\partial T}{\partial x}\right]+\frac{\partial}{\partial y}\left[k\frac{\partial T}{\partial y}\right]+\frac{\partial}{\partial z}\left[k\frac{\partial T}{\partial z}\right]+\emptyset \quad (6)$$

4 Result and discussion

CFD is a powerful tool for the analysis of fluid flows. It is a computer-based simulation technique providing an approximate two- or three-dimensional solution to fluid motion equations. The technique is characterized by a division of the region in which flow is to be computed the computational domain, into a huge number of much smaller domains referred to as mesh or grid cells. Complex geometries and time-dependent flows are readily handled. The solution consists of values of flow parameters of interest such as velocity or gas concentration, calculated at each of the grid cells. It provides a complete time-dependent picture of complex fluid flows.

4.1 The Layout of Squash Court for Configurations 1,2,3

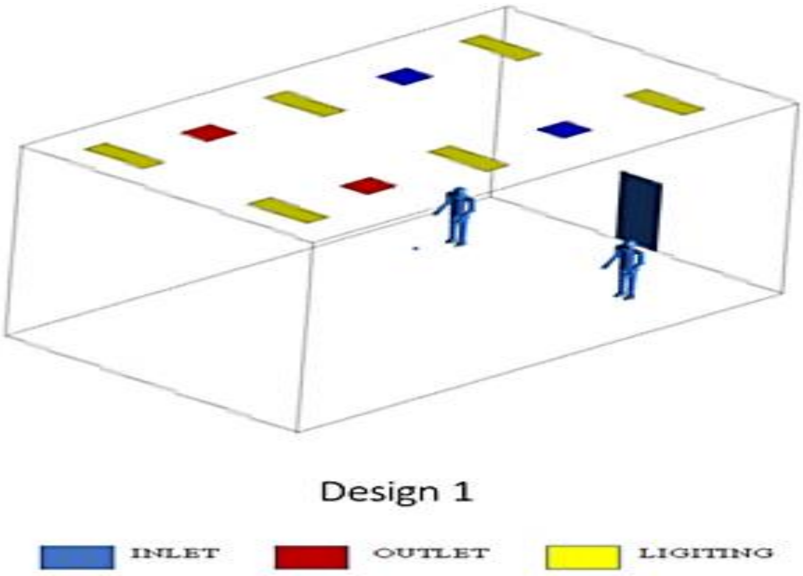


Figure 7: The layout of the squash court for configurations 1,2,3

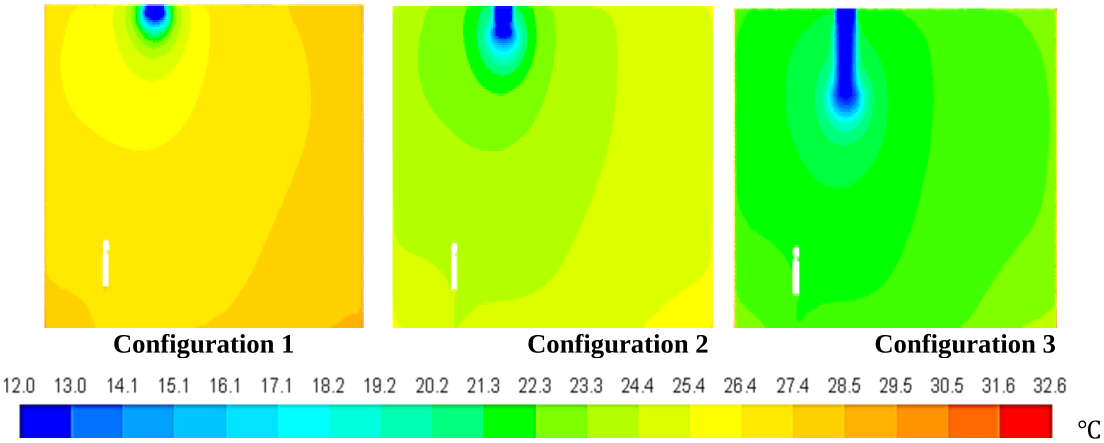
Table 1: Boundary condition of configuration 1,2,3

Boundary	Number of units	Properties			Dimensions
Lighting	6	4 w/m^2			130×30 cm^2
Inlet	2	Type	Velocity inlet		60 ×60 cm^2
		Supply air temperature	12℃		
		Supply air velocity	Configuration 1	0.87 m/s	
			Configuration 2	1. overs	
			Configuration 3	1.8 m/s	
Outlet	2	Type	Pressure outlet		60 ×60 cm^2
Walls	4	Temperature	35℃		Dimension of the court

Table 2: Locations of selected planes at the x-axis

Planes	Position	Notes
Plane 1 (blue)	1.8 m	Located under the inlet and outlet
Plane 2 (Yellow)	2.56 m	Ball plane
Plane 3 (Green)	3.4 m	Located near the middle of the court in the x-axis direction
Plane 4 (Red)	5 m	The same as the Plane 1

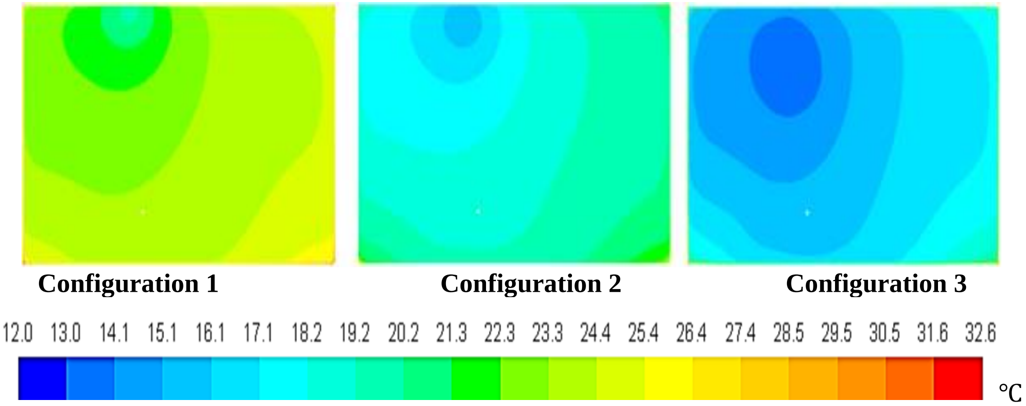
4.1.1 Temperature Distribution at Plane 1



Configuration 1 **Configuration 2** **Configuration 3**

Figure 8: Temperature Distribution at Plane 1

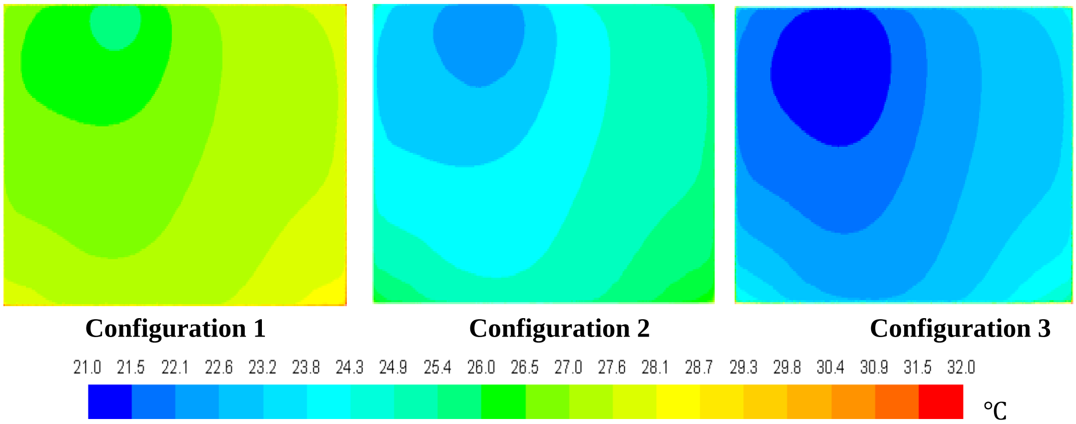
4.1.2 Temperature Distribution at Plane 2



Configuration 1 **Configuration 2** **Configuration 3**

Figure 9: Temperature Distribution at Plane 2

4.1.3 Temperature Distribution at Plane 3



Configuration 1 **Configuration 2** **Configuration 3**

Figure 10: Temperature Distribution at Plane 3

4.2 Selected Y-Axis Planes for Configuration 1,2,3

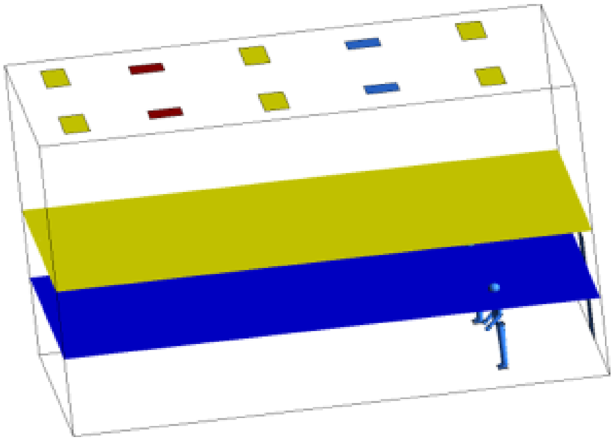
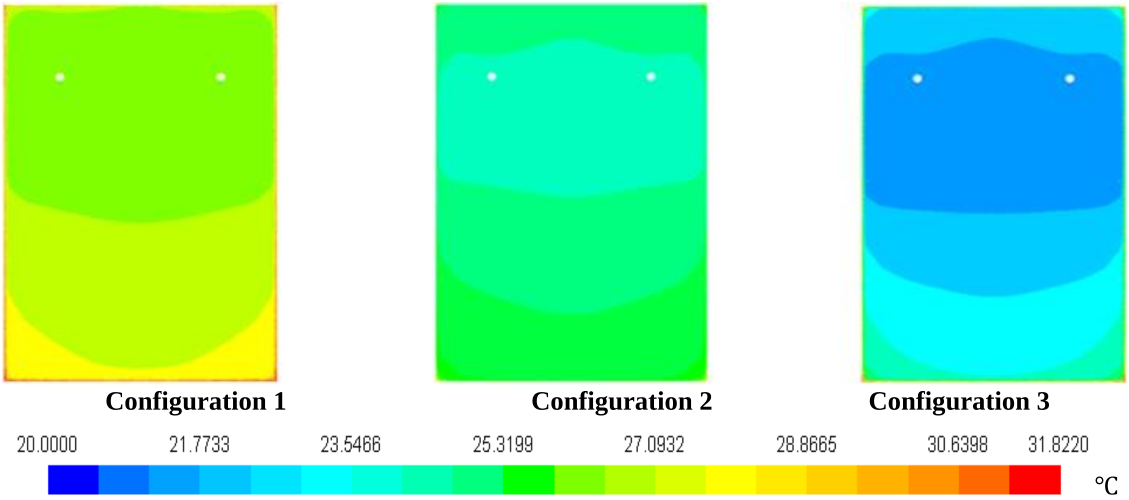


Figure 11: Location of selected y planes in design 1

Table *3*: Locations of selected planes at y-axis

Planes	Position	Notes
Plane 1 (blue)	1.85 m	Located At the player's head
Plane 2 (yellow)	3m	Located In the middle of the distance between the ceiling and the floor

4.2.1 Temperature Distribution for Plane 1 at Y-Axis



Configuration 1 **Configuration 2** **Configuration 3**

Figure 12: Predicated mean value (PMV) distribution for plane 1 at y-axis.

4.3 Predicted Mean Vote (PMV) Contours at X-Axis for Configurations 1,2,3.

4.3.1 PMV Distribution for Plane 1 at X-Axis

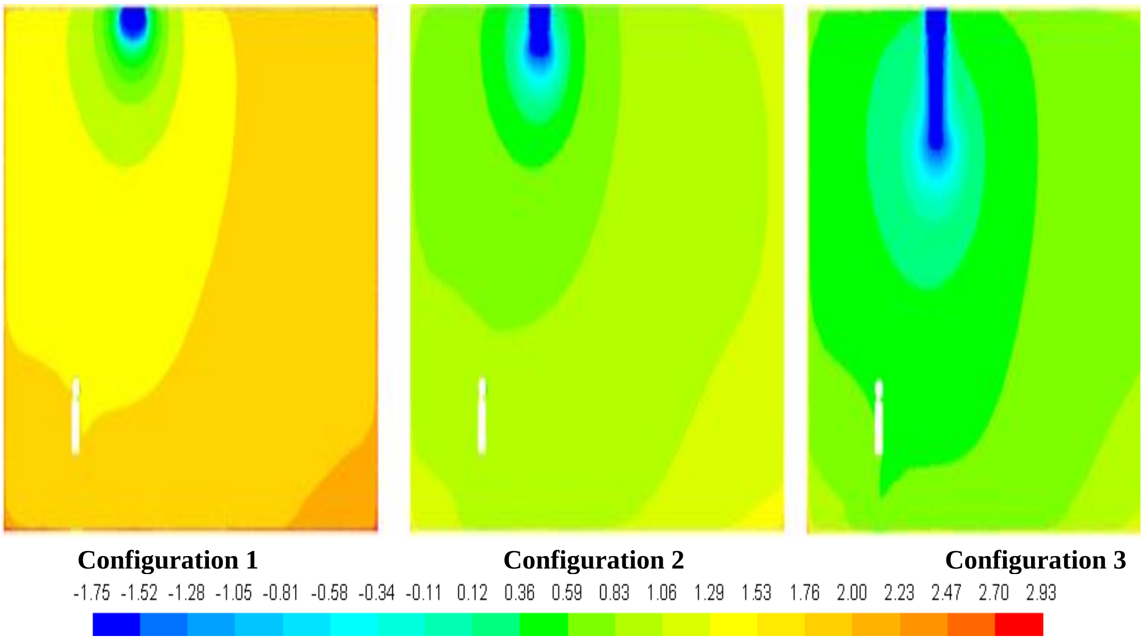

Configuration 1 **Configuration 2** **Configuration 3**

Figure 13: Predicated mean value (PMV) distribution for plane 1 at the x-axis.

4.3.2 PMV Distribution for Plane 2 at Z-Axis

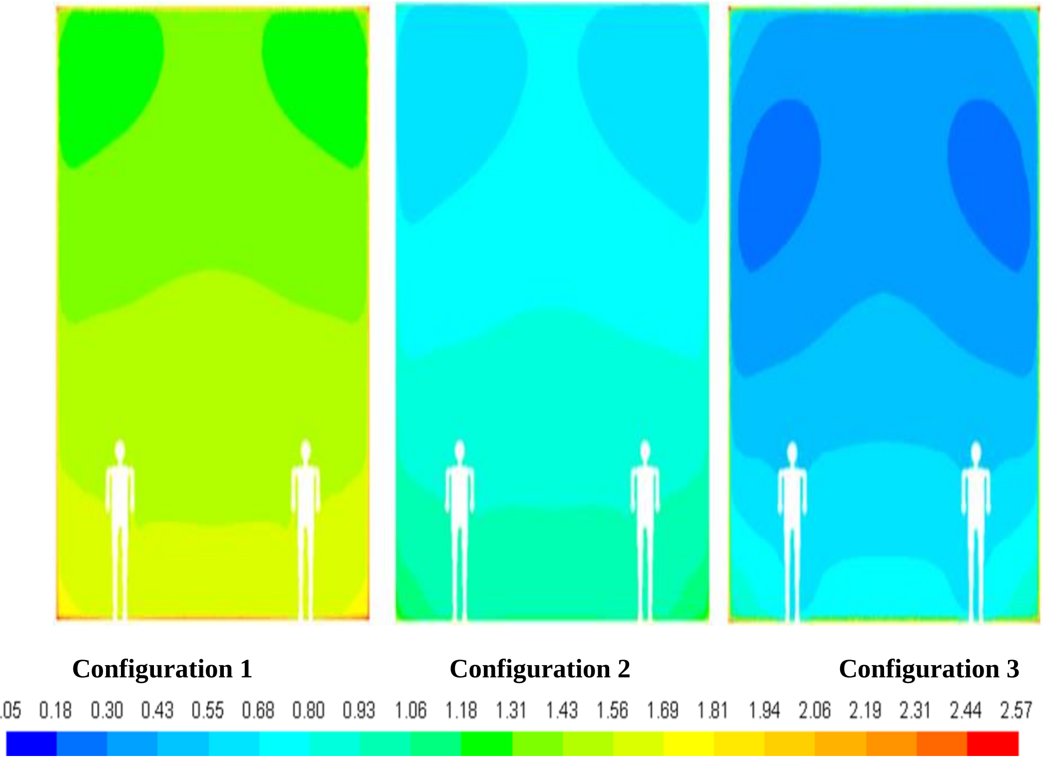

Configuration 1 **Configuration 2** **Configuration 3**

Figure 14: Predicated mean value (PMV) distribution for plane 2 at z-axis.

4.4 PPD Contours at Z-Axis for Configurations 1,2,3

4.4.1 PPD Distribution for Plane 2 at Z-Axis

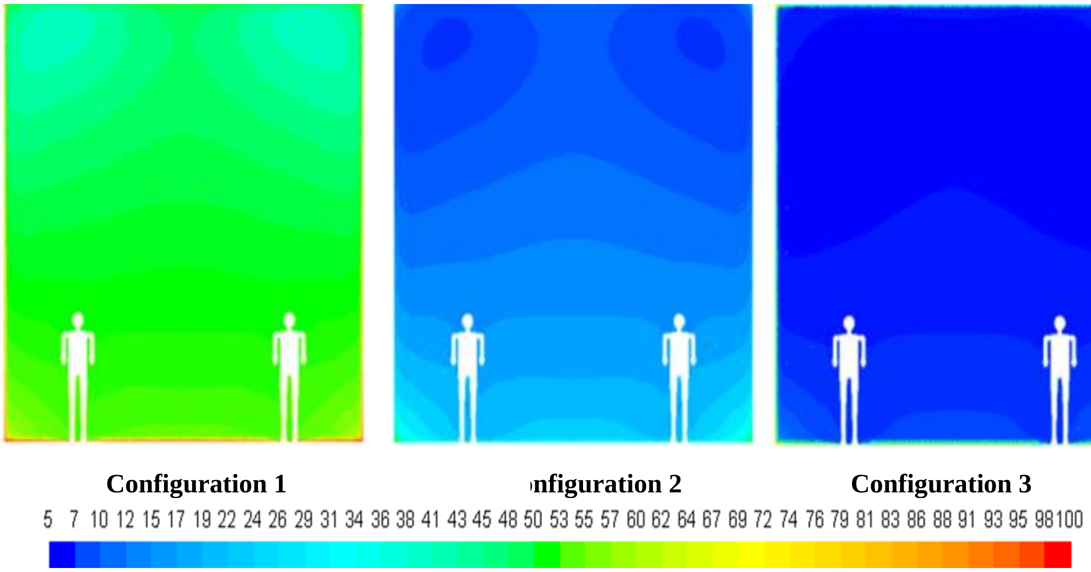

Configuration 1 **nfiguration 2** **Configuration 3**

Figure 15: Predicted percentage dissatisfaction (PPD) distribution for plane 2 at the z-axis

4.4.2 PPD Distribution for Plane 1 at X-Axis

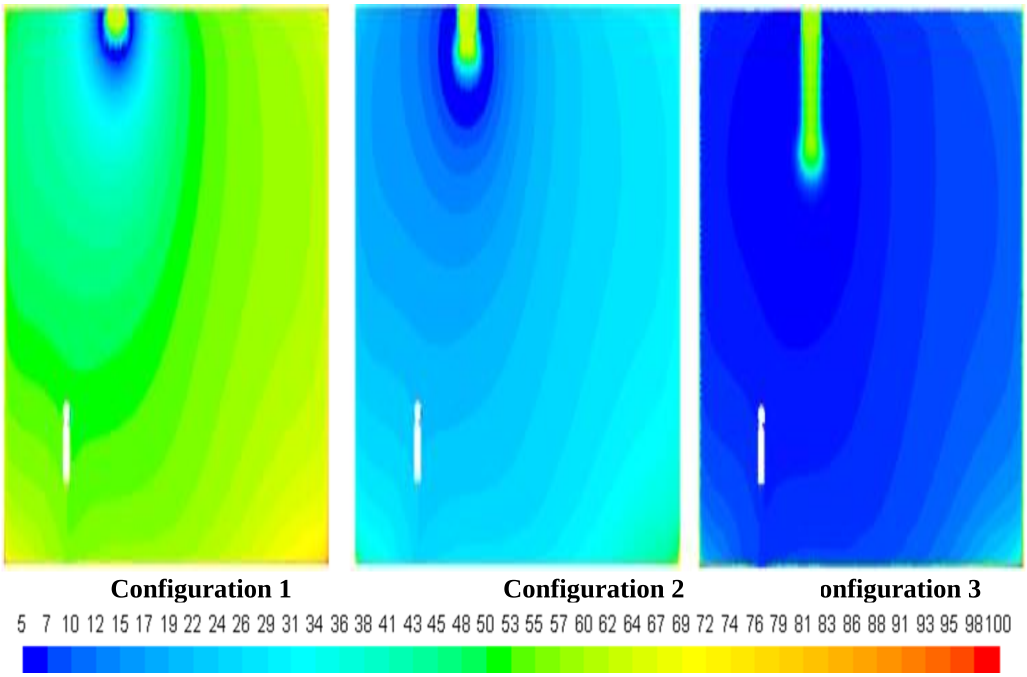
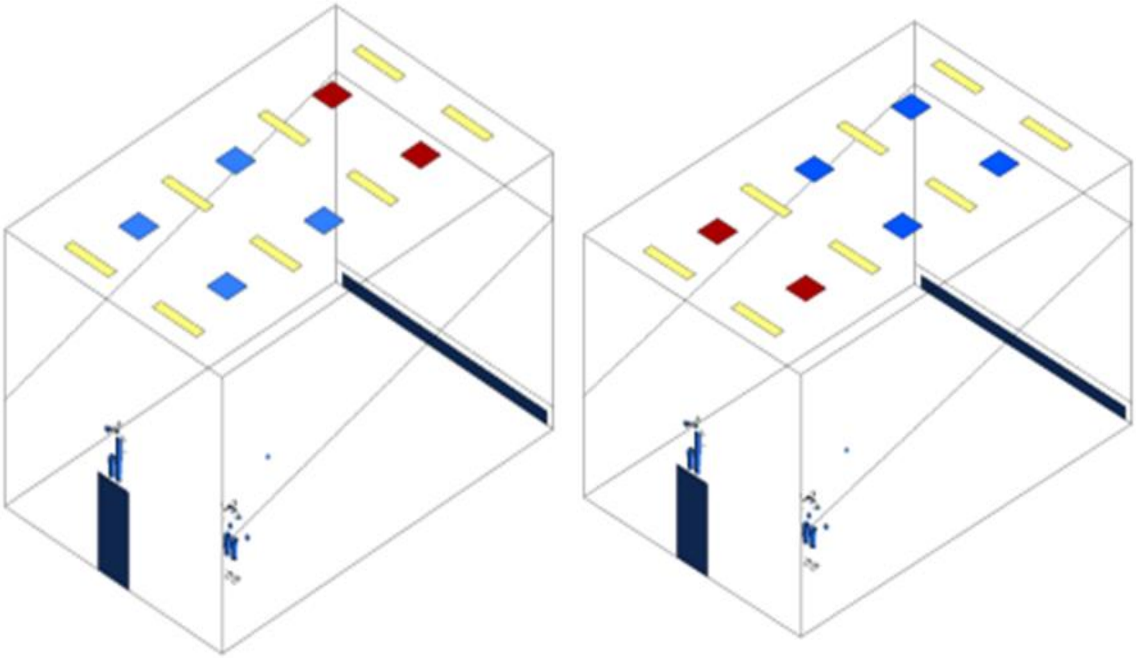

Configuration 1 **Configuration 2** **onfiguration 3**

Figure 16: Predicted percentage dissatisfaction (PPD) distribution for plane 1 at the x-axis.

4.5 The Layout of the Squash Court for Configurations 4 and 5



Configuration 4 **Configuration 5**

Figure 17: The layout for configurations 4 and 5

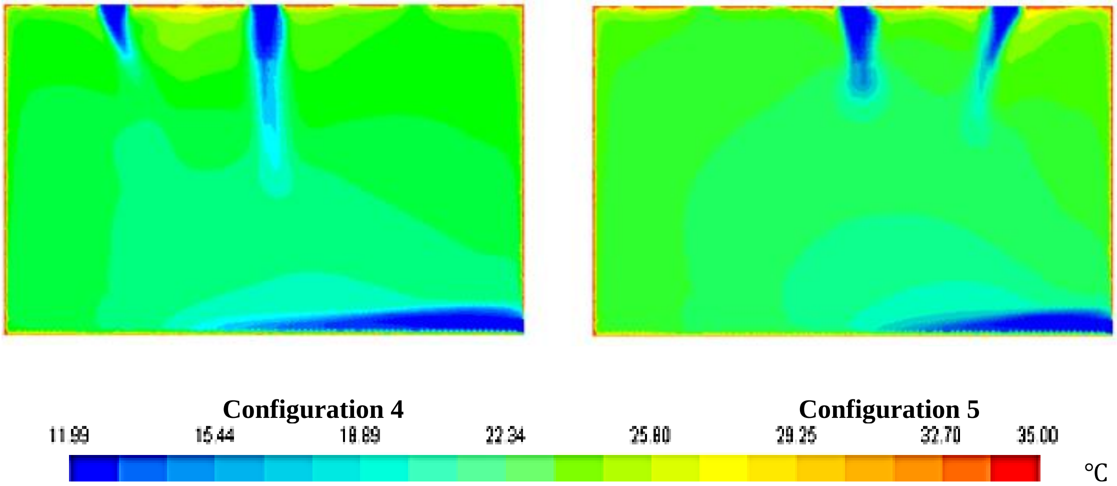
Table 4: Boundary conditions for configurations 4 and 5

Boundary	Number of units	Properties		Dimensions	
Lighting	8	2 w/m^2		130×30 cm^2	
Inlet	5	Type	Velocity inlet	Celling inlet	60 ×60 cm^2
		Supply air temperature	12℃	Tin wall inlet	6 m × 25 cm
		Supply air velocity	0.34 m/s		
Outlet	2	Type	Pressure outlet	60 ×60 cm^2	
Walls	4	Temperature	35 ℃	Dimensions of the court	

Table 5: Location of selected x-planes for configurations 4 and 5

Planes	Position	Notes
Plane 3	.3.5 m	Located near the middle of the court in the x-axis direction__
Plane 1	2.5 m	Located Under the inlet zone

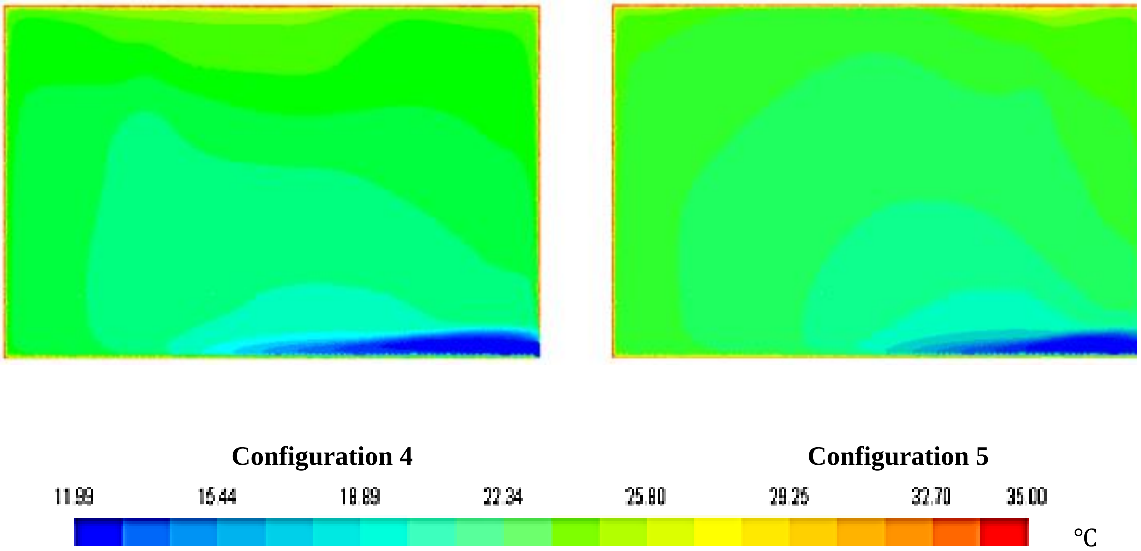
4.5.1 Temperature Distribution for Plane 1 at X-Axis



Configuration 4 **Configuration 5**

Figure 18: Temperature distribution for plane 3 at the x-axis

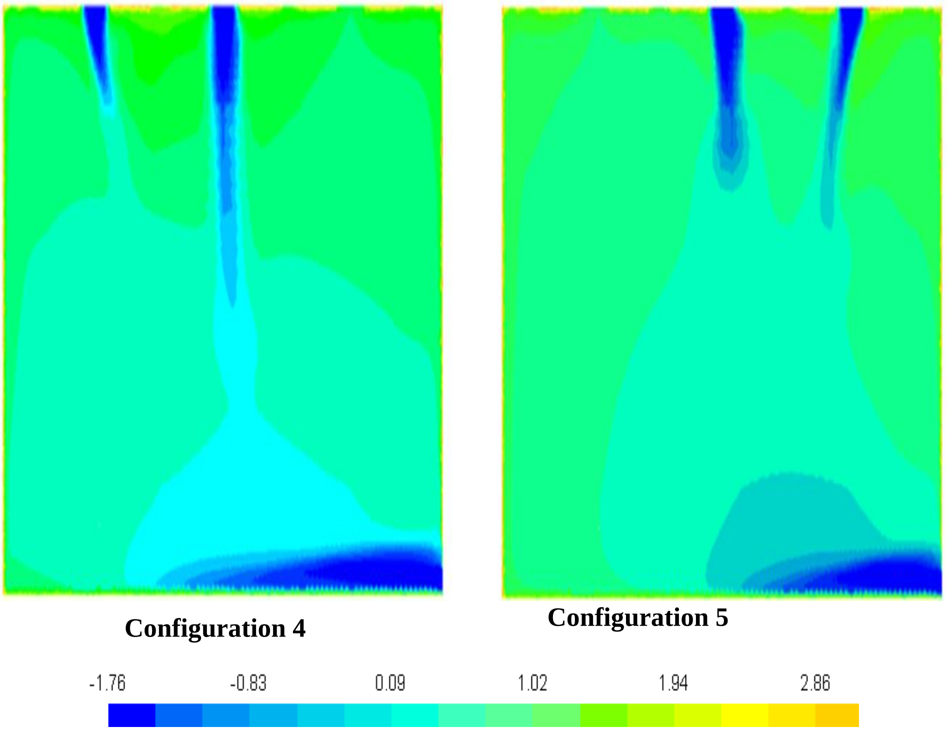
4.5.2 Temperature Distribution for Plane 3 at X-Axis



Configuration 4 **Configuration 5**

Figure *19*: Temperature distribution for plane 3 at the x-axis

4.5.3 PMV Distribution for Plane 1 at X -Axis

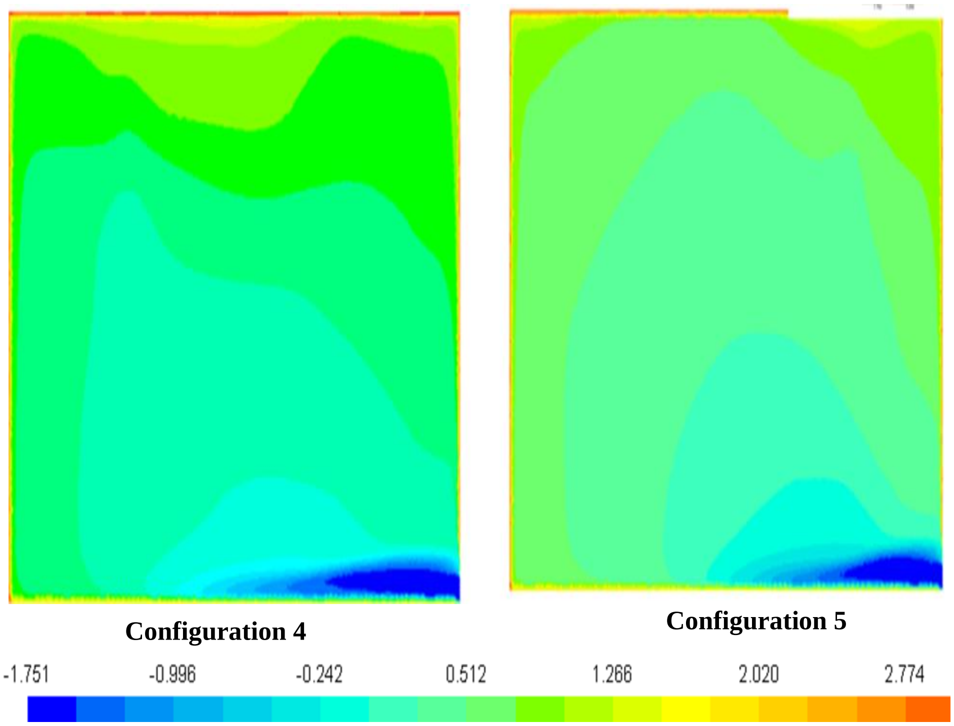


Configuration 4

Configuration 5

Figure *20*: Predicted mean vote (PMV) distribution for plane 1 at the x-axis.

4.5.4 PMV Distribution for Plane 3 at X -Axis



Configuration 4

Configuration 5

Figure *21*: Predicted mean vote (PMV) distribution for plane 3 at the x-axis.

The effect of the rectangular inlet for the first three configurations is too low and needs to reach a very high velocity that could affect the game of squash. The air inside the court is not distributed well, as most of the air goes to the near wall, which leads to dead zones inside the court. For configurations 4,5 the number of the inlet has been increased to reduce the inlet velocity.

The velocity in the first three configurations is becoming noticeable at an altitude of 4 m. It is rare for the players to play the ball to go through this high altitude to avoid the loss of points.

The number of the inlets for configurations 4 and 5 has been increased to reduce the velocity and get better air distribution inside the court. The number of inlets in the ceiling is 4 and 2 outlets and near the floor in the tin wall, an inlet has been added.

The only difference between configuration 4 and 5 is in the position of the outlet in configuration 4. The outlet is at the end of the court near the hitting wall, and in configuration 5 is at the other end of the court.

The difference in the result between configuration 4 and configuration 5 is in air distribution inside the court. Configuration 5 is the better one as the location of the outlet avoids eddies that occur at configuration 4

The ball temperature decreases as the temperature level decreases inside the court but is still within the required temperature range in both configurations.

Predicated mean values for the zone in which most of the movement of the players occurred at configuration 4,5 is between [-0.2,0.2]. That range of PMV achieves thermal comfort for squash players.

5 Conclusion

- Configuration 3 is the most satisfactory configuration among the first three configurations. It reached a range of temperature 21-22℃ among all the courts and relative humidity at 30-37 %, velocity < 0.2 m/s, and acceptable CO_2 level, and the ball temperature is about 45 ℃.
- The result for configurations 4,5 is better than the first three configurations, even with the low velocity of 0.36 m/s at configuration 4,5.
- The inlet in the tin wall is the main reason for that improvement in the result, as it made a better distribution inside the court. The additional rectangular inlet in the ceiling does not affect the court noticeably.
- The ball reaches 40 ℃ but is still within the acceptable range, which enables the players to keep playing without the need to stop the match to reheat the ball.

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