CIB World Building Congress 2019
Hong Kong SAR, China
17 – 21 June 2019

Investigating the indoor environmental quality of a-state-of-the-art tennis dome at a University campus in UK

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Abstract

With the growing increase in health and wellbeing awareness, fitness through sports activities is gradually forming an integral part of the life style of human beings. However, nature does not always provide the outdoor climatic conditions for these activities to thrive in cold climates such as the United Kingdom (UK). Sports complexes such as indoor tennis facilities (domes) are now extremely popular in local councils and universities throughout the UK. With an unpredictable variation in climate conditions, the *tennis dome* is the ideal solution for keeping the racket swinging all year round. A UK University currently houses a state-of-the art indoor tennis facility (dome). This is an Air-supported structure comprising of a multi-layered woven polyester fabric, designed with ventilation and climate control. The floor area of the facility is approximately 1871m^2, with a height of 10.5m to the apex. Since its installation, there has been concerns about the build-up of hot still air pockets in areas of the dome due to a lack of air movement, consequently affecting the indoor environment (IE) quality. Two methods have been used to investigate conditions within the facility over three seasons;

a) Experimental measurements of five IE parameters (i.e. temperature, RH, CO_2, lighting levels, volatile organic compounds (VOCs) and air velocity)
b) Numerical modelling using integrated environmental solutions (IES) and CFD software

The results show high temperatures of between 20℃ - 43℃ across seasons with low air velocities < 0.1m/s. Simulations from the models predicts, the predicted percentage dissatisfied (PPD) is above 30% in autumn and no better in summer. The CFD contours demonstrates that the environment is not well mixed, hence the need to implement forced ventilation to ensure the facility meets stipulated benchmarks. Nevertheless, moving into an era where dynamic construction is becoming more in demand, this ongoing research is envisaged to provide results that would inform future designs.

Keywords: Indoor environmental parameters, modelling and simulation, cold climates, United Kingdom,

1. Introduction

The temperate maritime climate of the United Kingdom (UK) which is cool, often cloudy, wet and slightly warmer in summer does not always provided the ideal outdoor climatic conditions for sports activities such as playing tennis. However, with the nations desire to enhance sports activities, indoor sports halls are now extremely popular.

The European Sport and Recreation Building Stock includes about 1.5 Million buildings in Europe, estimating that in the UK, within this sector Sport and Recreation Buildings account for up to 10% of annual energy consumption and represent 8% of the building stock in some countries and regions (Revel and Arnesano, 2014). Despite the varied use and design, Revel and Arnesano, (2014a) emphasised that sports facilities share some common characteristics with offices and other commercial buildings. However, they are unique in terms of nature, energy consumption profiles, usage patterns and comfort requirements. Depending on use (i.e. a swimming pool or a gym or a tennis dome, etc.) and applications, these buildings vary enormously in size supporting indoor zones, providing facilities for sports activities including dry and wet sports. Common to all of these is the indoor environment (IE) which in all facilities needs to be designed and controlled to ensure occupants feel comfortable to ensure their health is not negatively impacted by the environment. Doing so enables the building design to minimise dissatisfaction as far as it is reasonably practical (CIBSE Guide A, 2016). Nevertheless, IE is the least considered during the design phase of indoor sports facilities (ISFs).

Studies in most literature consider energy conservation issues of ISFs (Kampel et al, 2016; Panaras et al., 2018), the indoor air quality (Hsu et al, 2009; Levesque et al, 2015), the effect of weather (Lucena, 2017) the consequence on thermal comfort (Revel and Arnesano, 2014a) and thermal sensation (Revel and Arnesano, 2014b) Where modelling has been used to inform the design of the indoor environment (IE), the ISO-PMV methodology has been applied in buildings (Leong and Essah, 2017) and in sports applications (Revel and Arnesano, 2014b), whiles computational fluid dynamics (CFD) has been used extensively in the design phase of buildings (Essah et al, 2016; Panaras et al., 2018), but very few relating to sports facilities (Revel and Arnesano, 2014b).

From the literature considered above, considering the number of studies that investigated indoor sports halls and facilities, none contemplates the holistic effect of the indoor environmental quality (IEQ) on the athletes due to the inherent complexities incorporated in the design (including size, cooling and heating demand, etc) and functionalities (including athlete's metabolic rates, type of sports etc) of sports facilities. The proposed research aims at discussing the potential impact of the related IEQ constraints within a tennis dome. A simulation analysis was implemented to investigate the effectiveness of air movement and the installed heating solution. IES (Integrated Environmental Solutions), an energy and thermal simulation software was used for the simulation; to provide calculations and flow patterns within the tennis dome to investigate the effect of design constraints on performance. This research is ongoing hence it has not been possible to present all results in this paper.

1.1 Case Study: Air supported Tennis Dome

General Description

The ISF of study is a state-of-the art indoor tennis facility (hereafter called the dome) located on a university campus in the South East of England. The dome is an air-supported structure comprising of a multi-layered woven polyester fabric, designed with ventilation and climate control. The floor area of the facility is approximately 1871m^2, with an overall height of 10.5m. The external appearance of the tennis dome is ¾ green with the remaining ¼ and roof area being white (Figure 1). However, to reflect on most of the light to the playing surface, a ¼ of the internal skin of the dome is green and the remaining ¾ to the roof is white (Figure 2). The air-hall houses three full size tennis courts measured with dimensions 23.77m by 10.97m (length by width), while the total internal is 49.5m by 37.77m.

Figure 1: External façade of the air supported dome

Figure 2: Interior of the air supported tennis dome

Inflation of the air-hall is controlled by a centrifugal electric fan which blows hot or cold air, dependent on the season. This is located at the rear end of the dome with an orifice of 0.8m in diameter at a height 1.0m to the center from the floor. The ventilation design configuration has the extraction duct located 0.5m to the right of the supply duct which is at a height of 2m from the ground (orifice diameter of 0.6m). The ventilation is designed to produce air movement which would not disturb players but provide air changes of up to three times an hour, to avoid stale air from the IE. Heating of the air space is controlled by a thermostat which is expected to keep the playing area at a steady temperature of 10℃. This however, is not aligned to the design guidance of 12-16℃, noted by Sports England (www.sportengland.org), RH levels are not defined. This is supported by the International Tennis Federations (ITF) design guidelines which suggests that through an effective Heating Ventilation Air-Conditioning (HVAC) system in winter, the heating system should maintain the indoor temperature between 13-17℃, whilst in summer, the air conditioning should maintain an indoor temperature of 6-8℃ below the outside temperature with 55-60% humidity (www.itftennis.com).

In addition, the lux levels within the dome is a form of indirect lighting provided by twelve 2000W Halide lamps with dysprosium-iodide additive, with a 75% design reflectance of the ceiling. The dome is open to staff, students as well as members of the public seven days a week. Opening times range from 0700-2200 hours (weekdays) and 0845- 2100 hours (weekend).

2. Methodology

Two methods of investigation were used to address and investigate the IEQ of the dome including: in-situ experimental measurements performed over 3 seasons in 2018; summer (June - July 2018), autumn (September – mid- November), winter (mid-November – January) and numerical modelling to visualize flow patterns. However, only the summer and autumn data are discussed due to the ongoing winter measurements.

2.1 Experimental Set-up

The measuring quantities are five IEQ parameters: temperature, relative humidity (RH), CO_2 concentrations, lighting levels, volatile organic compound concentrations (VOCs) and air velocity. The information of the instrumentation presented in Table 1 includes: the type of instrument and its measuring characteristics. The position of the sensors is illustrated in Figure 3. It is noted that the installation of the sensors in such a large space is a complicated task, as mixing of indoor air throughout actual operation is not favoured because of the air-hall dimensions and the operation of the HVAC system considering the thermal stratification within the air-hall.

Altogether, 14 Lascar sensors measuring temperature and RH were installed in the dome and set-up to log every 5 mins. The sensors were placed at net level (at 1m height) and on the poles of the light lamps (at a height of 2m) bordering the air-hall. The sensors could not be attached to the internal skin of the dome due to the risk of destroying the facade.

Table 1: Characteristics of the measuring instruments used

Sensors	**Range**	**Accuracy**
Lascar USB Data Sensor	-35℃ to 80℃	± 0.55℃
	0 to 100%	± 2.25%
ATP LX-1309 Light Lux Meter	40 – 400,000 Lux	±5% below 10,000 Lux ±10% above 10,000 Lux
Onset HOBO CO_2 Logger	0 – 5,000 ppm	±50 ppm ±5% of reading at 25℃
TSI Q-Trak Monitor 7575-X & VOC Probe 986	1 to 2,000 ppm	1 to 3% of readings
Kestrel Meter 4200 Pocket Air Flow tracker	0.6 m/s to 40 m/s (1 second response)	± 0.1 m/s

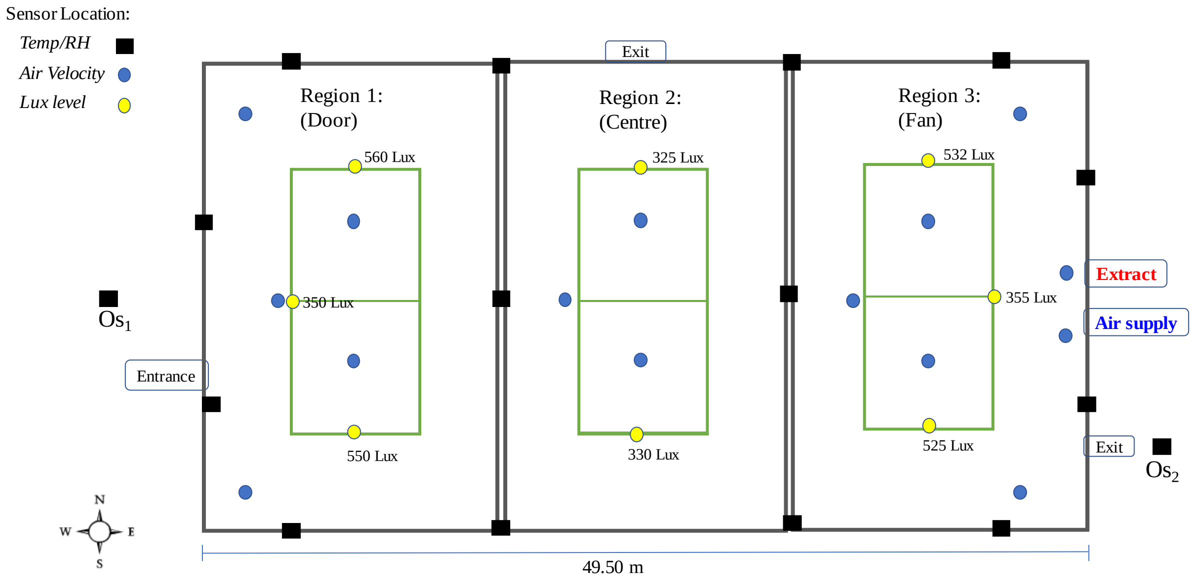


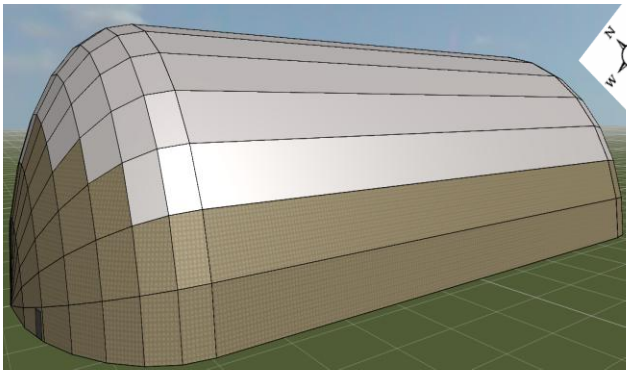
Figure 3:Schematic diagram of floor lay-out and location of monitoring sensor

Two sensors (Os_1 & Os_2) were also placed on either side on the fence about 3m away from the external façade at a height of 2m to capture the external conditions. The CO_2 concentrations were monitored for an hour and a half at different locations within the dome including: the centre and the obscure corners of the dome. Logging was at 5-minute intervals and the results were used to determine the air change per hour (ACH) in the dome. As with the measurement locations of the CO_2 concentrations, VOCs levels were monitored by focusing on those known to be often detected in the IEs (WHO, 2010; Alves et al, 2013). This includes: Isobutylene, Acetaldehyde, Acrolein, Benzaldehyde, Toluene and p-Xylene. The light levels were also monitored at sensor locations as illustrated on the floor lay-out in Figure 3.

2.2 Numerical Modelling

To be able to develop a model to support the analysis of the IEQ effects within the air- hall, documentation (section 1.1) from the observed hall, together with the real-time measurements were used to generate an IES model for simulation. The results from the real-time measurements and documentation in section 2.1 were used to calibrate the simulation model. Figures 4 and 5 show the geometry of the model. The construction of the air-hall which is contained under pressure with a polystyrene material was modelled in the same way using the IES software.

As boundary conditions for the model: number of people, weather conditions for the locality, profiles for the operational times and regime, foot falls, heating and cooling times were crucial to the model properly predicting the indoor conditions. The external weather data for 2017 was used in the model and temperature values are as illustrated in Figure 6.



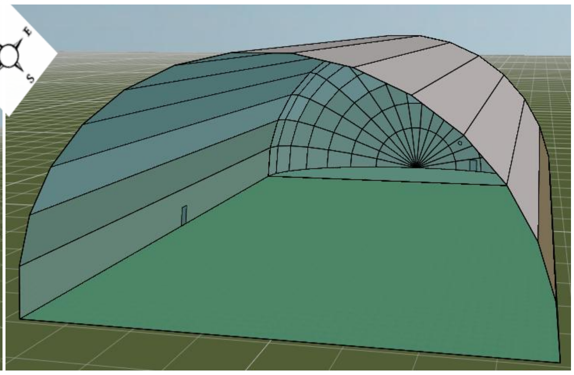


Figure 4:External façade of the simulated model *Figure5: Internal view of the simulated model*

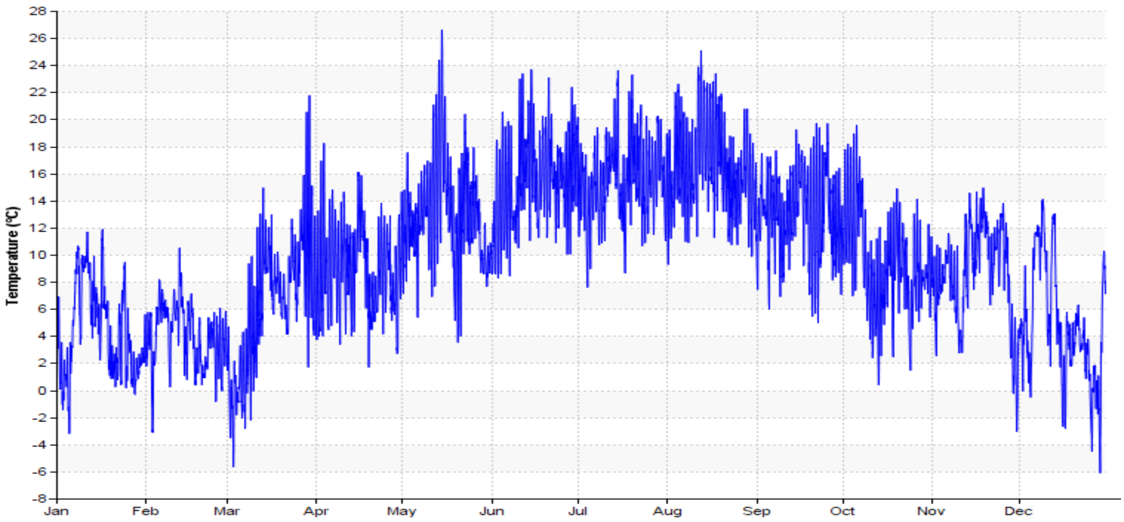


Figure 6: Outdoor temperature for the simulation model

3. Results

The aim of this research is to investigate the potential impact of the related IEQ within the air-hall of the tennis dome. To address these detailed analyses were performed starting with the experimental data. This was followed by the simulation analysis of the air-hall to investigate the effectiveness of air movement and heating solution. In this section, the resulting effect of the air movement within the dome is discussed. Using the IES software the yearly indoor conditions are predicted and its adverse effects on its potential effects on the athlete's is discussed.

3.1 Experimental analyses

Volatile Organic Compounds (VOCs)

Over the three seasons VOC levels have been measured. Since the installation of the dome in March 2018, the first VOC samples collated for the compounds considered (see section 2.1) was in June. The average, minimum and maximum levels obtained inside the air-hall after the sampling period are tabulated in in Table 2. Recommended guideline safe limit values (Table 2) has been set to protect public health when using sports facilities such as the one of study. Individual VOCs in the air-hall were mostly found to be within the safe limits apart from acrolein which was observed to be above the safe limit on average. It is not clear what caused the high concentration, but this is since being monitored.

Table 2: Summary results of the VOCs monitored in the air-hall

VOC	**Minimum** (ppm)	**Maximum** (ppm)	**Average** (ppm)	**Safe Limit** (ppm)
Isobutylene	0.2	0.5	0.31	250*[1]
Acetaldehyde	0.3	0.6	0.5	100*[2]
Acrolein	0.1	0.3	0.2	0.1*[2]
Benzaldehyde	0.02	0.02	0.02	0.042*[3]
Toluene	0	0	0	150*[4]
p-Xylene	0	0	0	150*[4]

*[1] *ICSC 1027 - ILO & WHO, 2017* *[2] *CDC - NIOSH Pocket Guide to Chemical Hazards Appendix G.*
*[3] *New Jersey Department of Health and Senior Services - NOTE: Odour limit used*
*[4] *Health & Safety Executive (HSE), 2000.*

Temperature and RH

High relative humidity and thermal amplitudes between nighttime and daytime highs were registered. Indoor temperatures recorded were higher across the air-hall (see demarcated regions in Figure 3) with notably higher temperatures (summer and autumn) at playing courts around the entrance door and supply fan (Figures 7 and 8). Considering design playing temperatures (section 1.1), 70% of the time in summer it was impossible to play tennis due to the air-hall temperatures ranging between 20 - 40℃. Whereas in autumn the dome was only considered playable 20-30% of the time with temperatures ranging between 5 - 25℃. These monitored temperatures are significantly high indicating the environmental conditions have not been maintained as per design standards as indicated in the graphs by the lower and upper specified limits (LSL and USL respectively). These high temperatures could be attributed to the inefficiency in the performance of the HVAC system which is evident in the low air velocities recorded in the air-hall.

In terms of RH, although ITF design guidelines suggest a range (section1.1) this is not clearly stipulated by the Sports England hence a grey area. As a result, for this study the acceptable limits of IE conditions for general building are also considered. Figures 9 and 10 illustrates the RH distribution in the air-hall. During the summer months the air hall only met ITF standards 10% of the time however, this increases to 80% of the time if generalized IE conditions are considered. The outcome is no different in autumn when considering ITF guidelines, but in terms of IE conditions, the air-hall only meets the criteria 60% of the time. These two parameters (temperature and RH) cannot be considered independent of each other hence from figures 7-10, the conditions do not meet the fundamental design criteria.

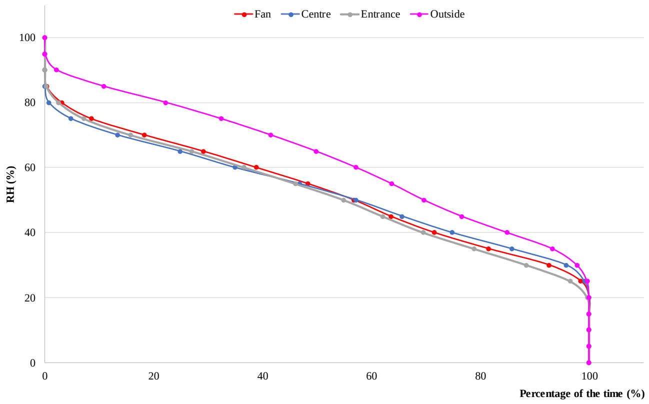


Figure 9: RH distribution in summer, based on regional zoning

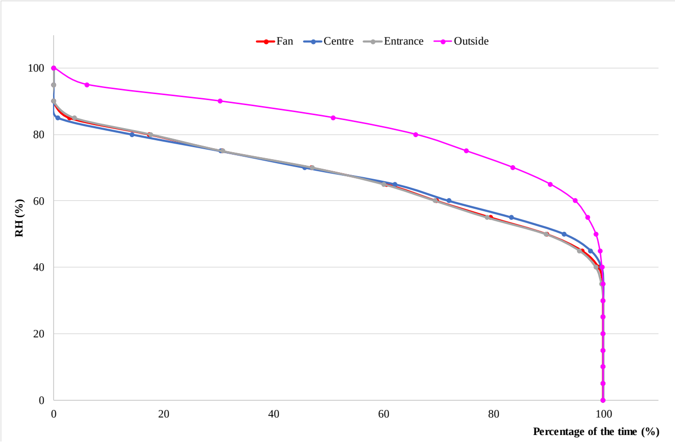


Figure 10: RH distribution in autumn, based on regional zoning

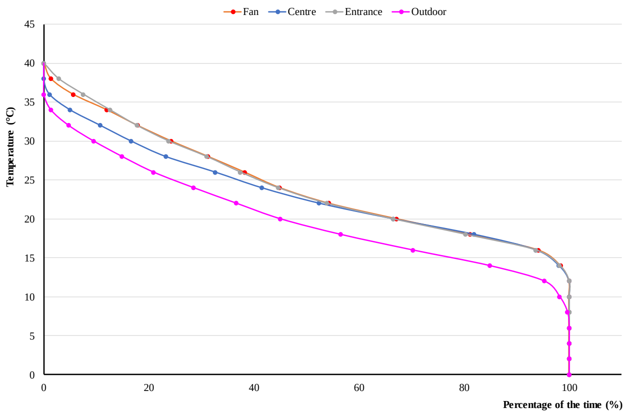


Figure 7: Air temperature distribution in summer, based on regional zoning

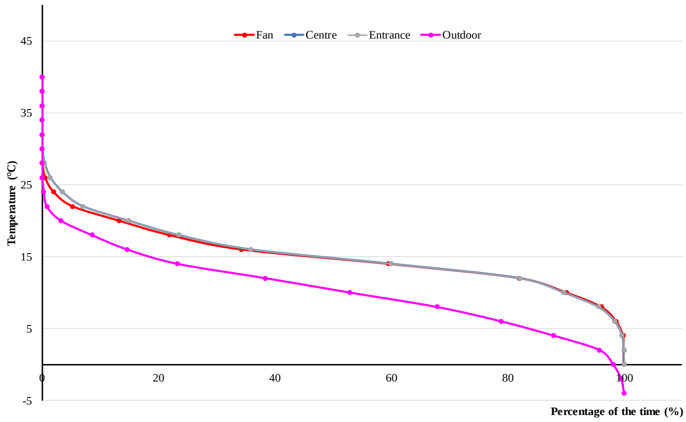


Figure 8: Air temperature distribution in autumn, based on regional zoning

3.2 Comfort Levels

Lighting levels and Air velocities

Documentation by Sports England and the Lawn Tennis Association (www.sportengland.org) state that the luminance in the principal playing area should be 600lux for a double skin and 500lux for a single skin. Figure 3 which shows that the luminance monitoring locations indicate good lighting levels on the outer courts but poor levels on the inner court. This may be due to the lighting layout within the air-hall which is outside the perimeter of the playing courts.

Air velocity measurements were also measured to be 0.1m/s on average across the air-hall (figure 3) but for measurements taken from the supply and extract outlets air velocity rates were 3.1m/s and 1.5m/s respectively.

Thermal comfort and comfort index

To understand the impact of the measured temperature and RH values on the athlete's, the human thermal comfort indices were calculated using the ISO-PMV method given in BS EN ISO 7730 (2005) and summarized in equation 1. The outcome was verified with the results generated from theCBE thermal Comfort tool (http://comfort.cbe.berkeley.edu/) with recommended metabolic rates for tennis players quoted at 3.6 met. A summary of the minimum and maximum instantaneous results obtained is shown in Table 3.

$$PPD = 100 - 95 \times \exp(-0.03353 \times PMV^4 - 0.2179 \times PMV^2) \qquad \text{Eq 1}$$

Table 3: Summary of seasonal PPD percentages according to the measured zones.

Region/Zone	**Summer (PPD)**		**Autumn (PPD**	
	Min (%)	Max (%)	Min (%)	Max (%)
Door	6	100	44	100
Centre	8	100	35	100
Fan	7	100	40	100

Details from all calculations using ISO 7730 shows that the PPD is between 70-80% of the time. This is further confirmed by the IES simulated results for the entire year as illustrated in Figure 11. The centre region nevertheless, demonstrates that it is relatively comfortable in comparison to other regions (Figure 3). Calculated values for summer and autumn are verified by the results illustrated.

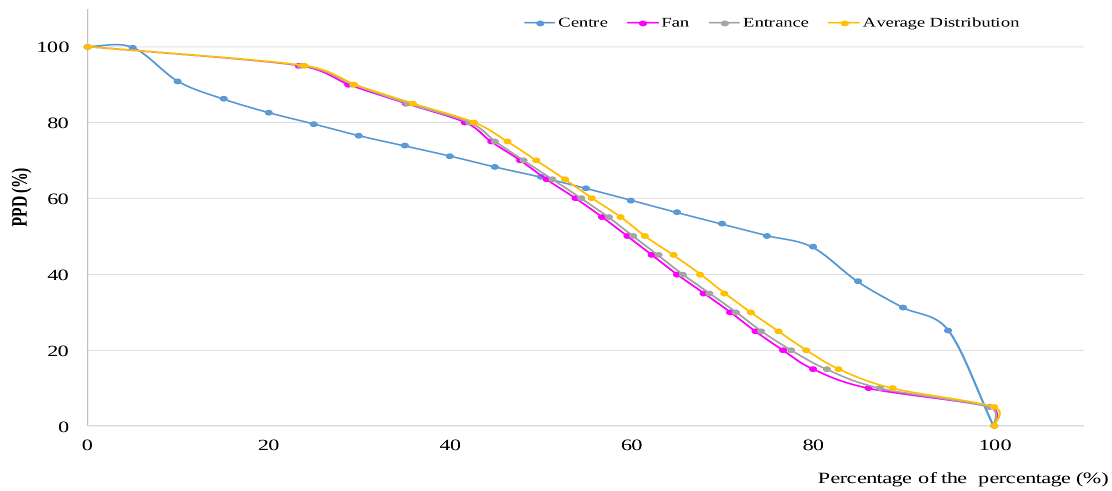


Figure 11: PPD year distribution in air-hall obtained from IES simulation

3.3 Numerical Analyses

The IES model was verified with experimental temperature values showing a deviation of ± 3%. This could be attributed to other boundary conditions which were not measured due to limitations and access. However, this demonstrated that the model is viable. From the IES software CFD analyses were developed to investigate the potential impact of IE conditions all year round. This was important to inform the operation of the dome.

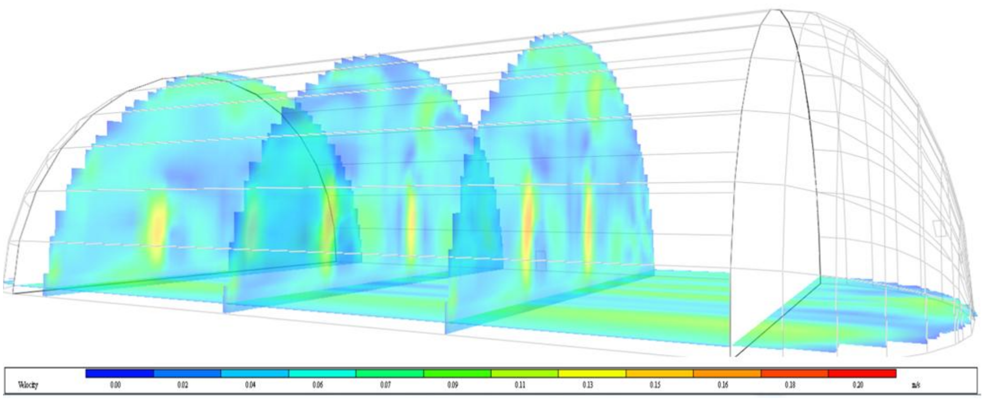


Figure 12: CFD contours illustrating air flow patterns in each region of the air-hall

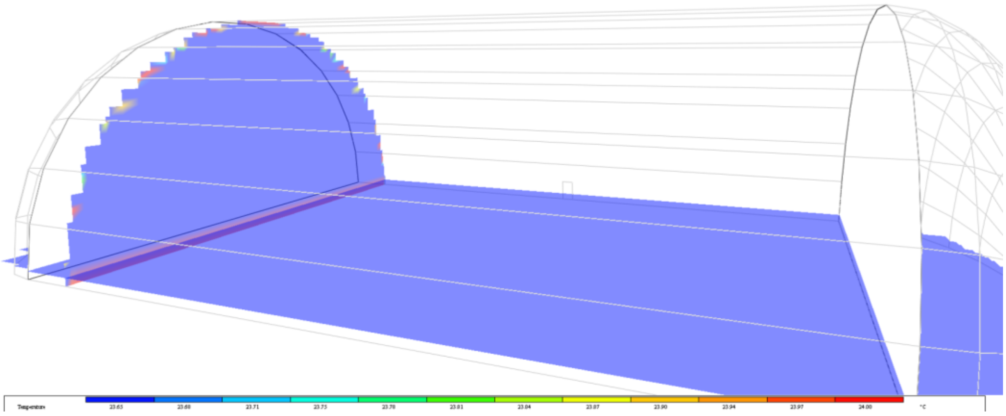


Figure 13: CFD Contour of temperature distribution along the playing plane and the door region

The CFD contours were developed from a plane along the courts at a height of 0.5m from the ground (Figures 12 and 13) for a typical day in summer based on the boundary conditions. Temperature distributions modelled were above 23ºC while's air velocities were approximate 0.1 m/s, aligning with the measured data. Thermal comfort levels demonstrated that the inner court was the best to play on while the other courts were significantly thermally uncomfortable.

4. Conclusions

Traditionally tennis is played outside during the spring and summer months. The purpose of the tennis dome is to prolong the tennis playing season by providing a climate controlled internal environment, which is not affected by external weather extremities such as rain and snow. The results demonstrated in this paper has presented an evaluation of the IEQ of the tennis dome for the summer and autumn season of 2018. Aligning the design to LTA and ITF guidelines, we conclude that there are significant climate control concerns for both seasons. In fact the results shows that the IE of the air-hall is not properly controlled by the HVAC system installed. This is evident in the summer temperatures of 20 - 43℃ and autumn temperatures of 5 - 25 ℃. From these values and other parameters, over 70% of the time PPD levels were above 60%. This is in part due to the lack of air movement in the dome.

It was observed that the ideal court to play on amidst all else is the central court. However, this court had the lowest lux levels which does not meet playing guidelines. VOC levels were acceptable with no concerns over the monitored period. It must however be noted that this research although still ongoing, the preliminary findings reported in this paper shows that there are significant design concerns which is likely to have adverse effects on the athlete's playing conditions. A reconsideration of the entire design set-up is recommended, especially the environmental control system.

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