Journal of Art, Architecture and Built Environment (JAABE)
Volume No.1 Issue No. 1 Spring 2018
ISSN: 2617-2690 (Print) 2617-2704 (Online)
Journal DOI: https://doi.org/10.32350/jaabe
Issue DOI: https://doi.org/10.32350/jaabe/11
Homepage: https://sap.umt.edu.pk/jaabe/Home.aspx
Journal QR Code:

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Online Published: April 2018

Article DOI: https://doi.org/10.32350/jaabe/11/01

Article QR Code:
Usman Awan

To cite this article: Awan, U., & Iqbal, M. (2018). Thermal comfort based performance evaluation and modification of spatial air movement by CFD in the case of Wales Millennium Centre, Cardiff UK. *Journal of Art, Architecture and Built Environment, 1*(1), 1–23.
Crossref

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
27	17	01

A publication of the
School of Architecture and Planning, University of Management and Technology, Lahore, Pakistan

Thermal Comfort Based Performance Evaluation and Modification of Spatial Air Movement by CFD in the case of Wales Millennium Centre, Cardiff UK

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Abstract

Air movement in any space is one of the main factors of human thermal comfort for the occupants. It is also related with the type of activity in that space, clothing the occupants are wearing and the ambient air temperature of that particular space. Wales Millennium Centre (main theatre) is designed for multiple performances-based activities. In recent years, it has been observed that when the main curtain of a stage is lifted, there is always a huge down draught of air coming towards the front rows of seating area, making it uncomfortable for the spectators sitting there. In this paper, multiple Computational Fluid Dynamic (CFD) simulations are performed using WinAir4 software. The research found that most of the time the ventilation system was working well but noticed a higher temperature at the back-seating area of the hall. The paper suggests appropriate locations of inlets and outlets which should have been given to address this issue. The paper presents some viable solutions for the uncomfortable conditions that can be improved by providing more supply of air at the back-seating area and extract points at the top of the main ceiling, by providing cooling fins under the ceilings and keeping the stage air supply off as per the results of simulations discussed.

Keywords: thermal comfort, CFD analysis, simulations, WinAir4 software

Introduction

In the main theatre of Wales Millennium Centre (WMC) Cardiff, U.K., users of the space especially the spectators complained of the down draught coming on to them while the stage performance was in place, causing discomfort due to high wind speed in relation to air temperature, activity and clothing they are wearing. This problem was mainly identified in the front seating area of the theatre.

Wales Millennium Centre (WMC), Cardiff is designed by architect Jonathan Adams. (Adams, 2017) Thomas Architects explains the thinking

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behind the design of Cardiff's new landmark. *'I believe that architecture can stand alongside the highest of the arts, provided it does what art is meant to do: to communicate, to connect with the imagination, to civilize. To do this a building like the Millennium Centre, the first national cultural institution to be built here for over a half century, must say something to the public about the state of our nation now and about our hopes for the future'*.

It is designed as one of the finest contemporary buildings in the capital city of Cardiff, Wales (Percy, 2017).

1.1. Cooling System

Dealing with the sudden large peak load imposed by approximately 2000 people is difficult. Assessments were made of cooling towers, borehole cooling, by water cooling and ice storage. Ultimately ice storage combined with roof mounted chiller plant was shown to be the most cost effective in terms of running cost and capital cost. The ice storage system allows the chillers to be sized for half the peak load with the ice bank providing the remaining cooling capacity (ARUP, 2017).

1.2. Heating System

1.5MW gas fired boiler plant supply the heating needs, serving perimeter radiators, AHU heating coils and fan coil units. Direct gas fired water heaters supply the hot water demand.

Figure 1. Glimpse of WMC source: websites

The main auditorium hall is to be used for opera, ballet, large scale dance, musical concerts, and for children's theatre of comedy and play. Main auditorium hall is named after Sir Donald Gordon, South African businessman and founding patron who donated £20m for WMC's build and performance programming. (Donald, 2018) This hall has the capacity of approximately 2000 persons (ARUP, 2017).

1.3. Other Points of Interest

Design team and contractors worked in co-location site office. Arup fire were able to give significant savings in terms of down rated smoke extract systems following CFD analysis. In total 65-person years were spent designing the building. The building weighs 45000 tonnes. Each ice storage tank holds 70000 litres (equivalent to about 9 million ice cubes). The volume of air moved by all the air handling units is approximately 100m3/s. The louvers' serving the auditorium handling plant were bespoke, and were made especially to co-ordinate with the wood finish on the rear of the building.

1.4. Ventilation Strategy

The displacement ventilation system has been used in the auditorium, which supplies fresh air, taking from the back side of the building. Inside the hall, it is supplied from underside of almost every seat. The outlet for air is provided at the bottom of every ceiling at each level. There is some supply of air from the ceiling on the stage. This supply is on only when there is no show and the curtain is down. The idea behind is to avoid the down draught that may occur when the curtain is lifted.

The total amount of air that is supplied in the hall is 20m3/s, and the same amount of air is being extracted from the vents. The temperature of incoming air is maintained at 20^{o}C in winter as well as summer. The speed of incoming air is about 0.5m/s, which is comfortable at this temperature. The air supply from each inlet is about 0.00154m3/s. During the winter season, the heating of air is done in the ventilation plant by passing the air through the region of hot water pipes. The heat is transferred through convection. During the summer season when outside temperature is higher, the Ice cooling system is used which takes heat from the incoming air and brings it down to 20^{o}C. The extract is not reused or mixed with the supply air to make sure that there is no possibility of contamination in the supply air (ARUP, 2017).

1.5. Observations and Brief Comments on the Adopted Ventilation System

1.5.1. Supply and extracts. The supply of fresh air comes from the back side of the building, from the lower grill and the extract is also on the same side at the top level. Only mechanical ventilation system is used in order to retain the control of sound, as a very calm environment is needed. The ventilation required cannot be attained by natural ventilation. There was no possibility of having natural ventilation since the hall is at the centre of the building with very little outside exposure.

1.5.2. Ventilation strategy. The ventilation design of the auditorium was crucial. It was aimed to provide enough fresh air for 2000 people at the rate of 10l/s/p and the total came out to be 20,000 l/s. Air inlets were designed to be unobtrusive. Noise levels were to be maintained

Figure 2. Internal view of main hall, external supply and extract openings, supply grills under seats

below the PNC 15 requirement of the client brief. (ARUP, 2017) Each seat was to be provided with the correct amount of fresh air for cooling and ventilation which is about 0.0015m3/s. The auditorium has a displacement ventilation system with grilles located under each seat. The grilles (supplied by Krantz) were tested extensively in an acoustic lab in Finland (reputed to be one of the quietest in the World) before they were accepted. Each grille location was set out individually to ensure that there were no clashes with the structure or the seat supports. Ductwork velocities were limited to 1.5m/s, resulting in extremely large ducts (2mx 2m) and the velocity of inlet air was about 0.5m/s (ARUP, 2017).

The aim of this research paper is to modify the air circulation in the main theatre in a way that it should not affect the user's comfort by not coming in contact at the seating level. The main objectives of this research is to make front rows experience less air speed coming on the people seated there and avoid down draught. How can the high temperature areas in the hall be identified and rectified by bringing the temperature within the acceptable and comfortable range? It is assumed that if the location and air pressure m/s of the inlets and outlets of the mechanical system are redesigned and relocated or more of them are added as per the level of the activity and the occupancy going on in the space, it will rectify the discomforting conditions by redirecting the air between supply and extracts.

2. Literature Review

Thermal comfort is a complex topic and the methods studied so far are only approximate**.** Research has shown that in the last 20 years' time there has been a shift away from physically based 7 scale Fanger's comfort model towards the acceptance of adoptive comfort model. (de Dear, Akimoto et al. 2013) There has been a shift from undesirable toward the desirable qualities of air movement as well. The effect of temperature in temporarily occupied spaces (TOS) such as supermarket was studied (Yu, Yang et al. 2015) in Tianjin and it was found that the temperature range of 16.9-17.4 ^{o}C was considered comfortable and highly desirable by the respondents in TOS. (Yu, Li et al. 2017), (Wu and Mahdavi 2014). The type of clothing and its distribution over the human body may also effect the comfort conditions, as studied in hyper market, Italy, and it was found that in this scenario the PMV index could be unreliable (Simone, Della Crociata et al. 2013). These studies show that in the temporarily occupied spaces like the one under study, the comfort conditions may wary from occupant to occupant.

Based on the study (Velt and Daanen 2017), it is recommended that if it is hot outside and the user comes inside, it's better to increase the internal temperature than the standard temperature. It will give user a more acceptable thermal sensation and vice versa if outside temperature is low. Hence, decreasing the inside temperature than the standard one gives user more comfort. The thermal comfort is also related with the age of the occupant and a study conducted on elderly people showed that neutral temperature was lower than the PMV temperature in winter, but in summer there was no big difference in the actual neutral temperature and PMV temperature. (Jiao, Yu et al. 2017).

The comfort temperature also relates to the climatic conditions of the region one is living in, the study (Zhang, Cao et al. 2017) presents different winter neutral temperatures for Europe, North America and China, 23.4 ^{o}C, 22.7 ^{o}C and 21.7 ^{o}C, respectively. Comfort temperature of occupants are related to outdoor air temperatures, and it may increase and decrease with low and high outdoor air temperature respectively. (Takasu, Ooka et al. 2017). Metabolic rate is one of the factors to determine the human comfort.

(Luo, Wang et al. 2018) argued that occupants BMI, sex, age are important factors which should be given due importance in estimating thermal comfort, and a related study area is to determine the comfort zones in buildings with reference to specific metabolic rates. So the range of thermal comfort is not a universal phenomenon. Instead, it depends on many factors, even on the mood of the occupants and their psychological well-being.

Many researchers have carried out CFD analysis using computer simulation techniques. A CFD analysis was performed in a church building to analyse the heat transferred through air to the human body and it was found out that radiant heat transfer is more effective than heating system. (Aste, Torre et al. 2017) CFD tool was used to evaluate thermal comfort in natural convection in an experimental room with controlled external conditions at the University of Perugia (Cinzia, 2017) and it was found that predicted mean vote (PMV) values are pretty similar to the CFD simulations. Effect of partition walls in the library space was analyzed by (Aryal and Leephakpreeda, 2015) using CFD and it was found that it had a significant effect on the thermal comfort of the occupants. Those in air conditioned space were feeling cold, while those who were not in air conditioned space were feeling warm. There was 24% increase in the energy consumption as well and it recommended the modification of air conditioning unit. Evaluation of thermal comfort indices for the occupants of the room was done by (Hajdukiewicz, Geron et al. 2013) using calibrated CFD modelling along with real time filed measurements and both of these confirmed satisfactory room conditions. Thermal comfort – CFD maps regarding mean radiant temperature were developed in retrofitting decision of a small educational building in Copenhagen with the thermal opportunities of moveable internal partitions (Naboni, Lee et al. 2017).

The effect of angularity of atrium walls was studied by (Shafiei Fini and Moosavi, 2016) and it was found that the combination of converging walls of lower storeys (below neutral pressure level) and vertical walls of upper storeys enhances their performance. Ambient air temperature and wind speed in an ancient tower building in Beijing was tested, installed with floor type fan coiled unit, using CFD analysis and it was found that the temperature of air was within acceptable range. (Qunli, 2017) To discover the discrepancies in the internal peak temperature, four full scale house models were tested with CFD analysis in Newcastle, Australia, and it was found that average discrepancy rate varied between 1-5 hours when compared with the actual scenario on ground. (Aimen,

2017) With the help of real scale model used for accessing natural ventilation, accompanying CFD simulations suggest that in atria down draught from its top may supress the heat rising up. (Ray, Gong et al. 2014) CFD analysis performed on light well as a source of natural ventilation revealed that it works better when cross flow is made possible at double level of well walls. (Farea, Ossen et al. 2015) Cross ventilation flow rates were checked by (Perén, van Hooff et al. 2016) using CFD analysis and it was found that for single span room the convex shape of roof is better than concave and straight shape, while for the double span room the reverse is true. It performs better when it has a straight roof. Having one sided wind catcher and window was found to be better than having two sided wind catcher with the help of CFD analysis (Montazeri and Montazeri 2018) CFD analysis showed that for the optimal performance of building, purging and charging plays an important role linked with the use of space and external conditions (Santos, Wines et al. 2018).

3. Methodology

WinAir4 software is used for CFD analysis of air movement in the main theatre. Input data file is created in the text format in the required sequence and values. This file essentially describes the geometry and boundary conditions for the problem to be modelled. In this software the space is made by the combination of small cells. The first item of required data defines the domain size; the number of grid cells needed in each dimension. It is up to the user to decide which dimension is which, but it is usual practice to have the X-Y axes as horizontal and the Z-axis as vertical. It is up to the user to define the necessary grid size; this must be done with the knowledge of the problem size and the level of detail required in the results. Generally, the larger the grid, the more precise the results, but the greater (and so longer) the calculation effort. In the current study, 1’x1’ cell size is chosen to get accurate results. Each cell is defined with its specific boundary conditions like temperature, pressure and wind speed (inlet and outlet flows). Heat generation from the occupants and all other sources are given actual values as per CIBSE standards. The positions of inlet and outlets are modelled as per actual location on site with the same rate of air flows at supply and extract point. 2-D representation of the space is shown in Figure 3 below. The supply of air can be seen in red colour under the seating and over the stage and extract is shown with blue colour close to ceiling in Figure 3. The software does use the control file, monitor cells (with specific conditions), cell wall blockages, cell face blockages to run the simulation of overall domain in the most effective way. The results of the simulations can be seen for multiple parameters like temperature, air movement, humidity level etc within the domain. The reason for the selection of this software is that it is validated and widely used for this kind of study. As domain is developed by attributing values to each cell, it is considered more accurate to run CFD simulations. Another reason of using this software was that the author had a valid licensed version given by Cardiff University, U.K. The spot light or beam light falling on the stage is kept static (as it is not possible to make it moving in the system), which may slightly effect the findings. The term 'system' or 'Domain' are used to represent the overall inner space under study. It must also be noted that when someone is sitting, the seat is being shown as a red spot (as source of heat, in most of the cases discussed latter).

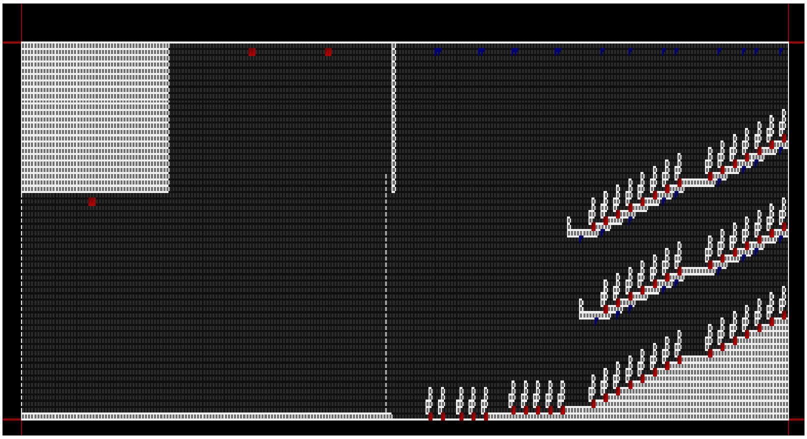

Figure 3. CFD model of main auditorium in WinAIR software

4. Simulation Results and Findings

4.1. Case 1: When Hall is Empty and Curtain is Down

Before the function starts, the hall is prepared as per the required conditions of temperature and air speed. When there is no one in the hall the temperature within the hall is maintained at 20 °C. The speed of the wind in front of the curtain is a bit high, and it reaches up to 0.46m/s, which can be seen in Figure 4 below (third illustration). The air is trying to escape below the curtain and hitting the front seating, as pressure is build up on the stage. But when this air reaches the front row its speed reduces from 0.46m/s to 0.26m/s which is quite comfortable. At the back of the hall the temperature and speed are 20 °C and 0.12m/s. This is the supply temperature and wind speed in the vacant space conditions.

4.1.1. Result. Before the activity in the hall the thermal conditions are well maintained and the space is comfortable for the occupant. With fresh supply of air in the hall, these are controlled conditions when there is no activity.

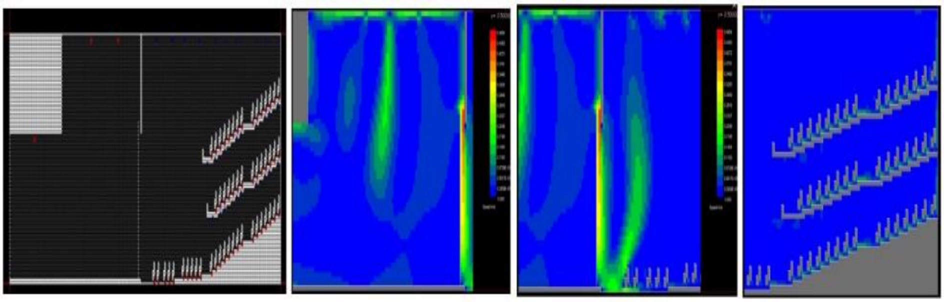

Figure 4. Case 1: simulation results, when hall is empty, and curtain is down

4.2. Case 2: When Hall is Full and Curtain is Down

When the hall starts to fill up by people, each one of them emitting 50-70W (first illustration of Figure 5) of heat into the system, this increases the inner temperature and it reaches up to 25°C, especially at the back-seating of the hall, middle and bottom level seats. The temperature for the last 6 rows is a bit high and may be uncomfortable. It varies between 23-25°C (fourth illustration). The air speed at the back is about 0.1m/s and on the top most tier it is 0.2m/s. At the end of the tier the air speed is about 0.37-0.45m/s. The speed at the front of the curtain is between 0.54-0.66m/s. The wind speed at the first seat is 0.45m/s and temperature is 20.5°C.

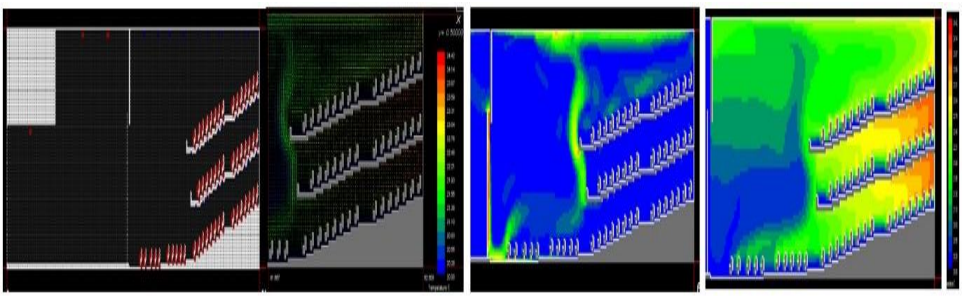

Figure 5. Case 2: when hall is full, and curtain is down, simulation results

4.2.1. Result. The temperature at the back of the hall is not comfortable and the wind speed at the first row may cause discomfort but temperature over there is about 20.5°C so it is acceptable.

4.3. Case 3: When Show is on and Stage Supply Fans are Off

When the curtain is lifted, the two volumes of air are mixed. The resultant temperature at the back of the hall is between 23-25°C and in most of the areas it is 22°C. Temperature at the point where spotlight is falling is very high. It is about 28.3 °C (this can be seen in the first illustration of figure 6, the temperature of air is high on floor where beam light falls) and at the first row it is 21.5°C. Wind speed in backstage areas is quite high at about 0.7m/s, on stage it is 0.4m/s. Wind is not hitting the first row seats and speed in the concerned areas is about 0.2m/s. This phenomenon can be easily seen in Figure 6.

4.3.1. Result. The overall temperature of the hall has increased up to 22°Cand it is worse on the stage which is about 28.3°C. It needs to be checked. Wind speed on stage and backstage areas is a bit higher at about 0.70m/s with a temperature of about 23°C.

4.4. Case 4: When Show is on and the Stage Supply of Air is on

As the temperature on stage increases, the supply on stage is turned on as a result (because of mixing of air volumes). Temperature at the back of hall lies between 22-24°C. Temperature in most of the areas is about 21°C. The temperature at the point where light is

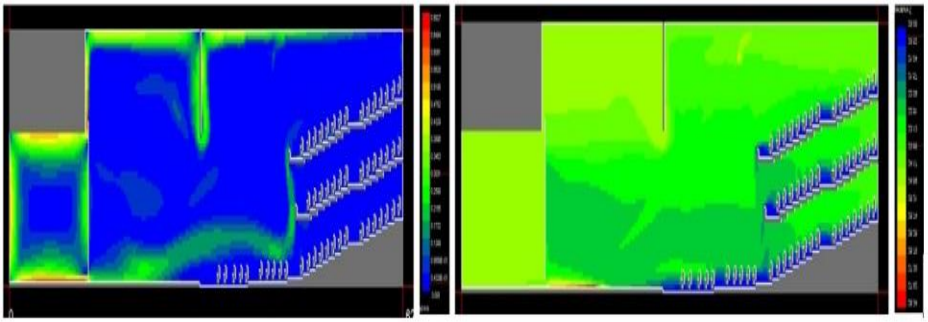

Figure 6. Case 3: when show is on and stage supply fans are off, simulation results

falling is about 24°C (it has decreased as fresh air is being supplied on stage, first illustration of Fig.7). Temperature at first row is about 23°C. The speed of wind at backstage area is about 0.4m/s. Its speed on stage is 0.64m/s and wind speed at first person is about 0.47m/s. Figure 7 explains the case.

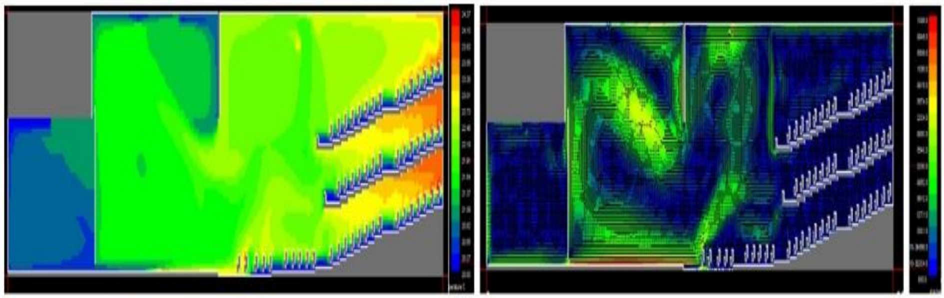

Figure 7. Case 4: when show is on and the stage supply of air is on, simulation results

4.4.1. Result. When the supply at the stage is on, the conditions in the hall are comfortable as compared to what they were earlier. The first row may experience some rise in temperature like 23°C but the wind speed is about 0.47m/s, so it may overcome it. It is better for the performer on the stage. The person sitting in the front row may feel a higher temperature but at the same time the speed of air is higher and by combing both parameters, it may be comfortable as claimed by some researchers (discussed in literature review).

4.5. Case 5: When Beam Light is off During Interval

The temperature at the back of the hall is bit higher like 23-25.5°C with wind speed 0.1m/s. Temperature at the first row is about 23°C and wind speed is 0.15m/s. The temperature in most of the occupant zone is higher as it is around 23°C, which is a noticeable change The air movement seen at the lower edge of curtain seem directed towards the extract point with higher temperature (second illustration of Fig. 8). The temperature at stage is about 22°C and wind is calm. There is no movement at the backstage area. There is an observed down draughts on the first 10 rows (second illustration of Fig. 8) with speed of 0.15m/s and temperature is about 22-23°C. Figure 8 illustrates the case clearly.

4.5.1. Result. It is uncomfortable for the back-seating area. There is a tendency of more wind flow in the occupant zone of hall with high temperature about 23°C. On stage the temperature is about 22°C, which is a bit higher for the activity area as there is more heat generation by the performers.

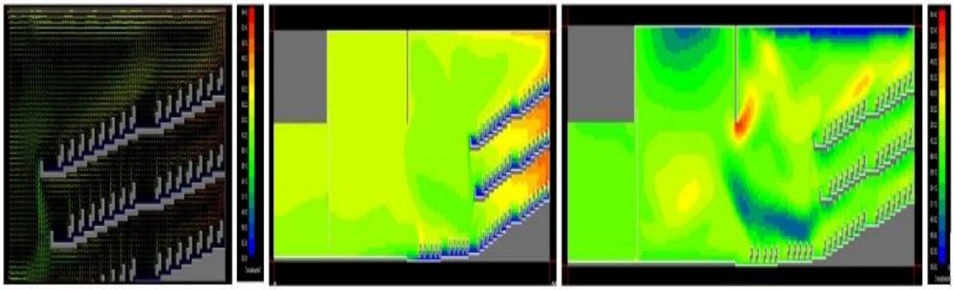

Figure 8. Case 5: when beam light is off during interval, simulation results

4.6. Case 6: When There is Half Occupancy in the Front Zone

When it is assumed that half of the hall is empty, i.e., half of the heat source is reduced, (second illustration of Fig. 9) then the temperature at the back-seating zone is quite comfortable between 20-21°C (as now there is no occupancy). The temperature above the occupant is about 22-23°C. On stage there is high temperature about 27°C (third illustration of Fig. 9). There is more wind speed pressure at the back stage area which is about 0.7m/s. There is a tendency of wind to flow towards the back-seating zone of the hall which is vacant and the wind blows over the front seated people with a speed of 0.2m/s at the temperature of 22°C. Figure 9 illustrates the case.

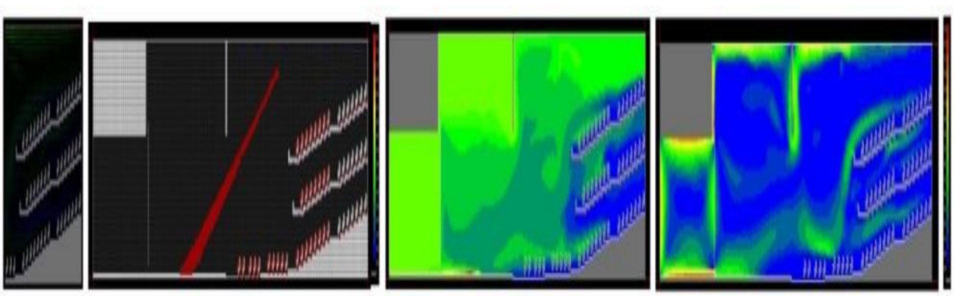

Figure 9. Case 6: when there is half occupancy in the front zone simulation results

4.6.1. Results. This is a bit comfortable condition in the back seat area of the hall. Temperature over there is within the comfortable range. There is a noticeable change in the wind flow pattern which is towards the back of the hall passing the occupant zone.

4.7. Modification Done to Rectify the Problem

In the following section, the researcher has done some modification of the mechanical system by adding some supply and extract in the domain. A number of modifications were done but only those which caused some improvements are presented here in this study.

4.7.1. Case 7: when some supply is given at back of the hall and some extract in the same zone. After analyzing the overall air movement in the domain, the researcher has started to look for some solutions to bring temperature and wind speed within acceptable range. Case 7 discusses the scenario when some alterations are done by adding supply and extracts (some supply is given at stage floor). The temperature at the back seated zone is about 20-22°C. The temperature of stage is about 26°C. The temperature at the first row is surprisingly 25°C, the air from the stage is dragging towards the occupant zone. The speed of wind at first row is about 0.24m/s. There is a down draught on the first two rows. Figure 10 is explaining the case clearly.

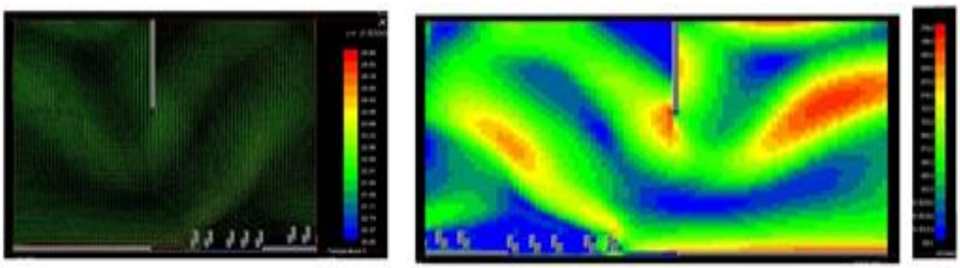

Figure 10. Case 7 when some supply is given at back of the hall and some extract in the same zone, simulation results

4.7.2. Results. By giving more supply at the back-zone area the temperature decreases and comes in the comfortable range. The most noticeable point is more heat dragging from the stage area towards the first rows of the occupants.

4.8. Case 8: When Some Supply is given at Back of the Hall and Some Extract at the Top Ceiling

The temperature at the backstage area is about 20-22°C. Maximum temperature is on the stage which is 29°C. The temperature at the front row is about 22°C which is less than before. The wind passes over the occupant zone with the speed of 0.2-0.26m/s and does not cause any draught on the occupant zone. (Figure 11).

4.8.1. Results. When some supply is given at back of the hall and some extract at the top ceiling. This is a comparatively more controlled condition since the temperature of most of the occupant zone is within the comfortable range. The wind speed in the occupant zone is also very calm. The problem remaining is the high temperature of the stage. By strategically adding supply and extracts the problem of down draught on the front rows is solved (second illustration of Fig. 11).

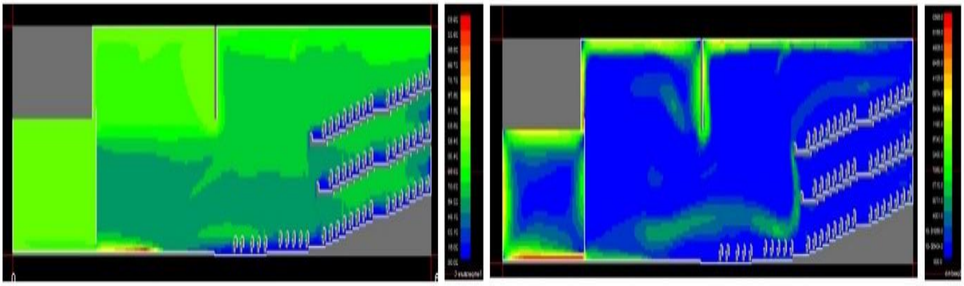

Figure 11. Case 8: When some supply is given at back of the hall and some extract at the top ceiling, simulation results

4.9. Case 9. When We Put Some Cooling Fins at the Ceiling and the Supply of Air at the Stage is off

By giving some cooling fins at the ceiling which takes 720W/m of heat out of the domain, we get the comfortable conditions.

4.9.1. Results. The temperature at the back of the hall is quite controlled between 20-22°C. The overall temperature of the hall is within the range of 20-23°C. The temperature at the stage area is 22.5°C.

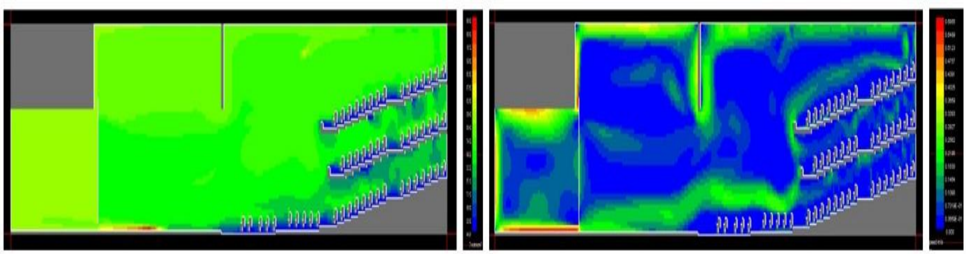

Figure 12. Case 9: when we put some cooling fins at the ceiling level and the supply of air at the stage is off, simulation results

At the part of stage where beam is falling the temperature is 28°C. The wind speed within the seating area is quite comfortable at about 0.1m/s. On the stage area, there is movement of air. At the backstage area, the wind is 0.6m/s. The hall has become comfortable at all the seating areas. The wind speed is within the acceptable range. The problem left is with the temperature on the stage.

4.10. Case 10. When the Cooling Fins are provided and the Supply Fans on the Stage are on

The temperature at the back seats of the hall is between 20-23°C which is bit higher than before. The temperature at the backstage is about 20°C. The temperature on the stage is about 21.5°C and at the area of beam fall it is 23.5°C. There is no wind movement on the seating persons. The speed of wind is higher on the stage at about 0.7m/s and it is hitting the first seating with a temperature of 23°C, when the cooling fins are provided and the supply fans on the stage are on. The other places in the hall are quite calm in terms of wind flow (Figure 13).

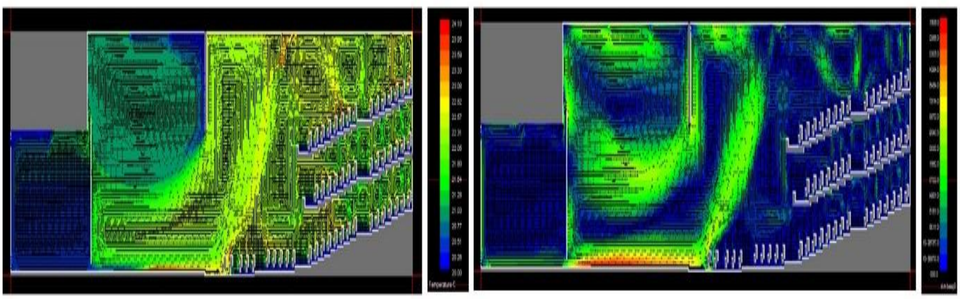

Figure 13. Case 10: when the cooling fins are provided and the supply fans on the stage are on, simulation results

4.10.1. Results. In this case the temperature over the stage is controlled to some extent, but there is a slight increase in the temperature which is about 23°C at some places over the seating area. The first row of the seating will feel some air movement, with the temperature of about 22°C. It may not cause discomfort.

5. Summary of Findings

Stage Area. In all the cases when beam light on the stage is on, the temperature of the stage increases too much. The temperature reaches up to 25-29°C on stage area when the performance is going on, which is not acceptable. Because the performing activity itself heats up the place. The wind speed on stage is a bit high which may give comfort. This is the case when static light is falling on some spot, but in reality, the light keeps on moving. So, the conditions would come close to comfortable range.

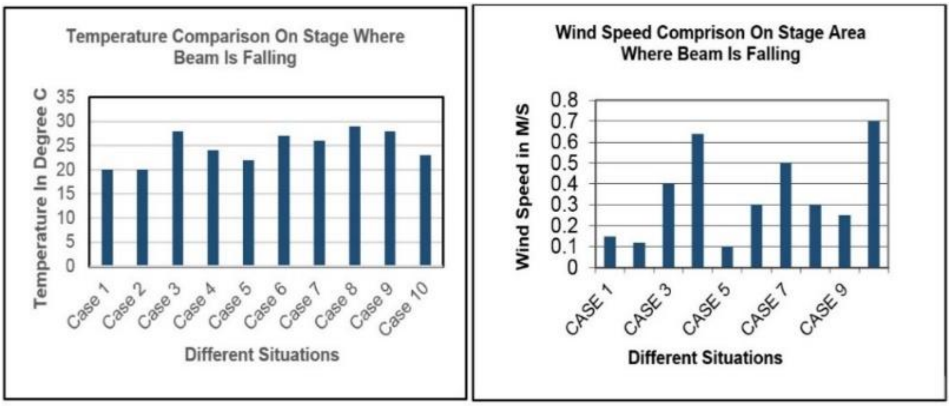

Figure 14. Temperature and wind speed comparison on stage area

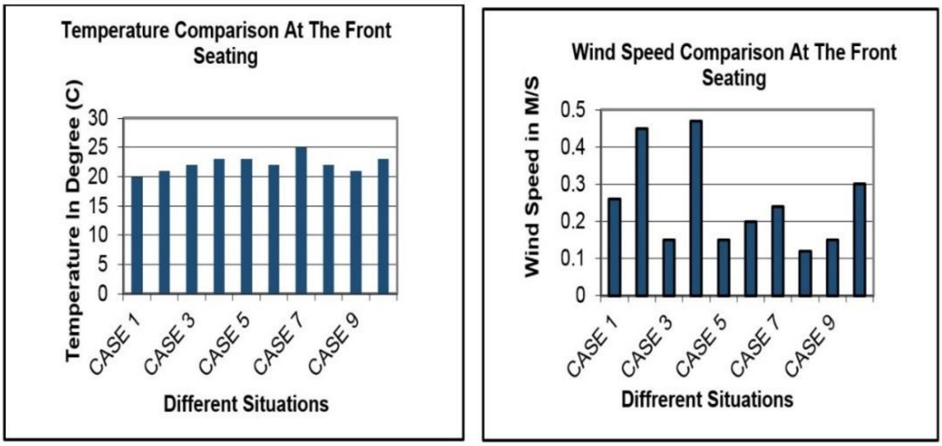

Figure 15. Temperature and wind speed comparison on front area

Front Zone. The temperature conditions on the front seating is within the comfortable range that is 22°C on average and wind speed is about 0.26m/s. There is a possibility of down draught when the supply of air is on from top of the stage. But this is not cool air which may cause discomfort to the people sitting on the front because the supply air is maintained at the temperature of 20°C. In this case, the warm air from the stage is dragging towards the seating area with a speed of 0.4m/s which may not cause discomfort.

Middle Zone. In the middle area of the hall the temperature is comfortable in almost all the situations which is about 22°C. Wind speed is also controlled which is about 0.2m/s. There is very little chance of down draught in this area. In some cases, wind is blowing in the middle area but it is above the seating level.

Rare Zone. The temperature at the back seats of the hall is usually high for the people seated over there. It reaches up to 25°C, but by applying some fresh air supply at the back on the wall and by installing some cooling fins below the ceiling, the temperature comes down within the comfortable range which is about 21-22°C.The wind speed at the back is just calm, about 0.14m/s, so the provision of cooling fins or some supply at back is necessary.

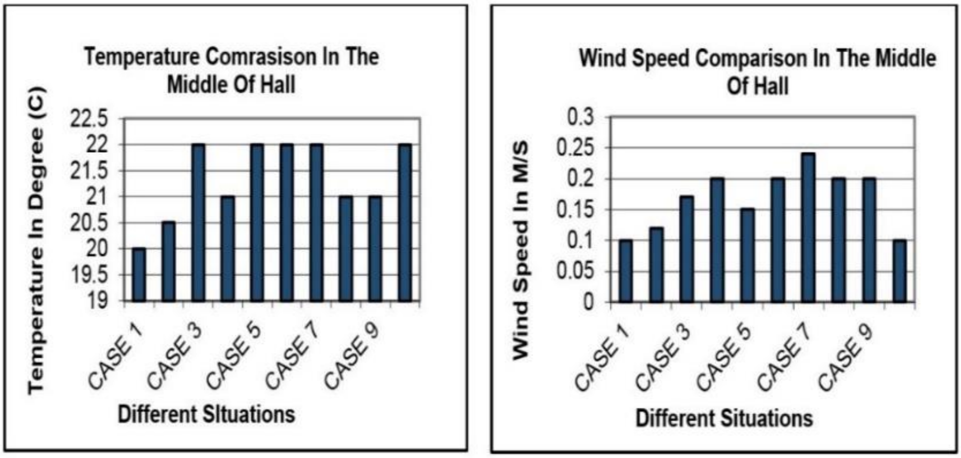

Figure 16. Temperature and wind speed comparison on middle area

The collective data as shown in the table1 below explains the temperature and wind speed in the main hall (under study) observed when different cases were studied. It must be noted that the combination of air temperature and wind speed provides comfort conditions to the occupants, under certain clothing and activity level. Generally, temperature of 20-22°**C** and wind speed of 0.2m/s is considered comfortable but it is mainly related to the clothing of spectators, which would vary during different seasons of the year.

Table 1

Temperature and wind speed at different areas of main hall under different conditions

Sr.	Cases (as taken in the study)	Temperature (°C)				Wind speed (m/s)			
		Stage	**Front**	**Middle**	**Rear**	**Stage**	**Front**	**Middle**	**Rear**
1	Case 1: when hall is empty and curtain is down	20	20	20	20	0.15	0.25	0.1	0.1
2	Case 2: when hall is full and curtain is down	20	20.5	20.5	25	0.12	0.45	0.11	0.1
3	Case 3: when show is on and stage supply fans are off	27	22	22	25	0.4	0.15	0.17	0.12
4	Case 4: When show is on and the stage supply of air is on	24.5	23	21	24	0.62	0.47	0.2	0.14
5	Case 5: when beam light is off during interval	22	23.5	22	25	0.1	0.15	0.15	0.1
6	Case 6: when there is half occupancy in the front zone	26	22.5	22	21	0.3	0.2	0.2	0.14
7	Case 7: when some supply is given at back of the hall and some extract in the same zone	25.5	25	22	22	0.5	0.25	0.25	0.1
8	Case 8: When some supply is given at back of the hall and some extract at the top ceiling	29	22.5	21	22	0.3	0.12	0.2	0.12
9	Case 9: when we put some cooling fins at the ceiling level and the supply of air at the stage is off	27	21	21	21	0.25	0.25	0.2	0.12
10	Case 10: when the cooling fins are provided and the supply fans on the stage are on	23	23	22	23	0.7	0.3	0.05	0.14

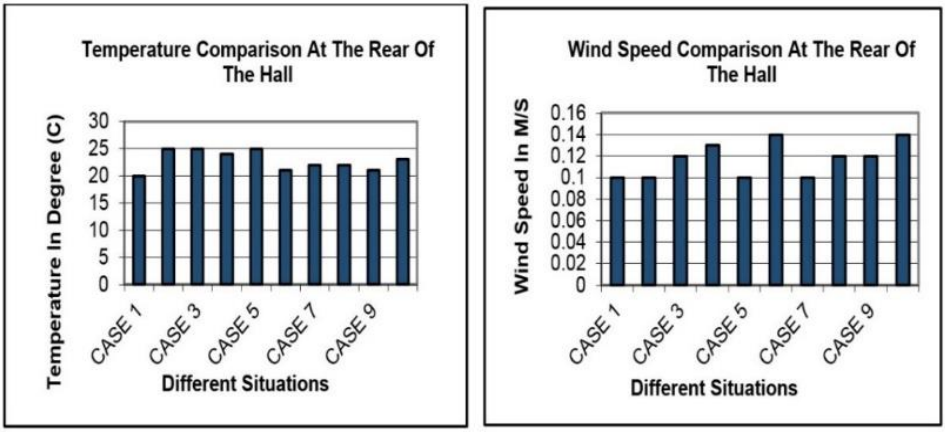

Figure 17. Temperature and wind speed comparison on Rear area

6. Conclusion

The CFD analysis of any space gives us clear idea about the air temperature, air speed, humidity and any other related parameters. It is a very useful tool to assess the volume flow mechanism in the system. In the current study undertaken, the WinAir analysis shows that the ventilation principle followed in the auditorium is working well. The environment within the hall is maintained by the supply air throughout the year (by controlled temperature and air speed). These controlled conditions seem to act well until there is no activity and occupancy in the auditorium, but when people start to get in the space (adding some heat in to the system) and activity starts, there is some rise in air temperature. In some places, it is being catered by the wind speed but at some other places, especially at the back-seating zone, the temperature is a bit higher (See case1-6).

7. Recommendations

The analyzed space conditions suggest some modifications in the system. The uncomfortable conditions can be improved by giving more supply air inlets at the back-seating zone and extracts at the top of the main ceiling, and by providing cooling fins under the ceilings and keeping the stage supply off, therefore the temperature of stage should be handled separately. The part of the stage where beam light is falling can be made with some material which can absorb heat falling on it. It's better to close the stage supply when show is on. The air supply in and out of the building has a short circuit, so it must be explored further (See case 7-10).

It is further recommended that to attain comfortable indoor conditions, multiple scenarios must be studied and conditions simulated. Based on these findings, mechanical systems should be designed. In this case study, the displacement ventilation system was adopted with the understanding of maintaining comfort conditions, but the transitions, phases and conditions such as the time when the hall is being occupied, activity interval, different levels of occupancies, varied activities, should also be considered in the design phases of mechanical system.

Acknowledgement

The Author would like to thank the following as they were the main sources of information required to conduct this study**.**

1-Arup, 4 Pier head Street, Capital Waterside, Cardiff CF10 4QP

2-Capital Percy Partnership, East gate building, new port road, Cardiff, Wales

3-Cardiff University, Architecture department for giving licenced version of Winair4 software and acting as resource for the research.

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