APPLICATION OF PHOENICS TO ATHLETIC HALLS WITH HVAC VENTILATION

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ABSTRACT

The commercial general - purpose Computational Fluid Dynamics (CFD) code PHOENICS is used to study the indoor environmental conditions of a large, mechanically ventilated, athletic hall. The indoor space of the building was simulated in the PHOENICS environment and computations were validated against experimental data obtained during a ten-day campaign in the hall. Data included measurements of airflow characteristics at different indoor locations under different ventilation conditions. Having obtained good agreement from comparing computed and experimental results, different ventilation scenarios of air-conditioning, heating and cooling, were applied in the model to investigate the air velocity and temperature patterns prevailing in the hall in each case. Computed results showed dynamic airflow and temperature patterns significantly altering with the different considered scenarios. Temperature stratification was evident, while distinct recirculating vortices characterized the airflow fields originating from the ceiling air inlet fans of the ventilation system.

KEYWORDS

CFD model, large enclosure, HVAC, indoor conditions, IAQ.

INTRODUCTION

In the last decades indoor air quality has become a public health concern. Research community have concentrated on the measurement of pollutants concentrations in closed spaces such as offices and homes (Lee et al (2002)) with a view to compare different indoor environments and identify pollution sources. Other studies have dealt with the relation of indoor pollutants concentrations to ventilation characteristics (Guo et al (2004)). At the same time CFD codes have become a useful tool in the research field of air quality. They have been applied to environmental studies of wind flow and pollutant dispersion around buildings, to investigations of indoor airflow fields for building design and optimum ventilation purposes (Xing et al (2001)) as well as to simulations of pollutants dispersion in working areas for health and safety reasons (Duci et al (2004)). However, few studies combine theoretical and experimental approaches and little has been done on studying environmental conditions inside large enclosures such as stadiums and athletic halls where many people congest and athletes train and compete while their performance can be affected by the quality of breathing air. Good ventilation and air quality conditions in such places are very important. Since metabolism is intense, supply of fresh air is necessary for achieving comfort conditions. Therefore, this study investigates numerically and experimentally the airflow, temperature and pollutants concentrations fields prevailing in a large mechanically ventilated athletic hall under different ventilation conditions.

METHODOLOGY

Experimental Procedure

A ten-day period experimental campaign in the frame of a national research project took place in an indoor basketball hall built in 2000 and situated in the eastern suburbs of the urban complex of Thessaloniki-Greece. Parking areas and auxiliary athletic facilities surround the hall, while the close vicinity includes heavy-traffic roads at about 500m and the sea at about 1km to the southwest. The building is 30m high, the surface of the arena is 1125m^2 and the capacity of the hall is 8,000 spectators. The windows are normally closed and the Heating – Ventilating – Air Conditioning (HVAC) system operates when necessary. Measurements were taken at different locations in the hall with the HVAC system in operation. Instrumentation included DANTEC FlowMasters (type 54N60) for spot mean air velocity, temperature and turbulence intensity measurements at sets of 1-min. Surface temperatures of indoor materials were measured with infrared thermometer (COLE & PARMER, type 08406) and CO_2 concentration measurements were taken with portable instrumentation (IAQRAE PGM – 5210, indoor air quality monitor).

Theoretical Model – Initial and Boundary Conditions

The PHOENICS CFD code (Spalding (1981)) solves the time averaged conservation equations of mass, momentum, energy and chemical species in steady three-dimensional flows.

$$\frac{\partial}{\partial t}(\rho\Phi) + div\,\{(\rho\upsilon\Phi - \Gamma_\Phi\, grad_{\,\Phi})\} = S_\Phi \qquad (1)$$

where ρ, υ, Γ_Φ and S_Φ are density, velocity vector, “effective exchange coefficient of Φ” and source rate per unit volume, respectively. The discretization of the domain is followed by the reduction of the previous equations to their finite domain form using the “hybrid formulation of the coefficients” and the solution technique employs the SIMPLEST algorithm (an improved version of the well-known SIMPLE algorithm). The standard k-ε turbulence model is applied, while buoyancy effects are considered. To improve convergence, under-relaxation was used.

A three-dimensional rectangular enclosure was considered in Cartesian coordinate system as seen in Figure 1. For symmetry reasons, only one fourth of the indoor space was modelled. The dimensions of the objects modelled are real and geometry is as detailed as possible according to the building’s plans and the mechanical ventilation system’s blueprint, always taking into account computational efficiency. The domain size is 45m x 45m x 22m and it includes 81 rows of spectators’ seats, 23 circular air-inlet fans at the ceiling and 8 air-outlets close to floor level.

The cases studied are as follows and the specific settings for each case are given in Table 1. (1) Basic Case: This case corresponds to a selected day from the experimental campaign. The hall is empty and the HVAC system operates in the air-conditioning mode, without heating or cooling. (2) Heating Case: This case is same as Basic Case, while the HVAC system operates in the heating mode. (3) Cooling Case: This is a hypothetical case of a typical summer day in Thessaloniki-Greece. The hall is considered empty and the HVAC system operates in the cooling mode.

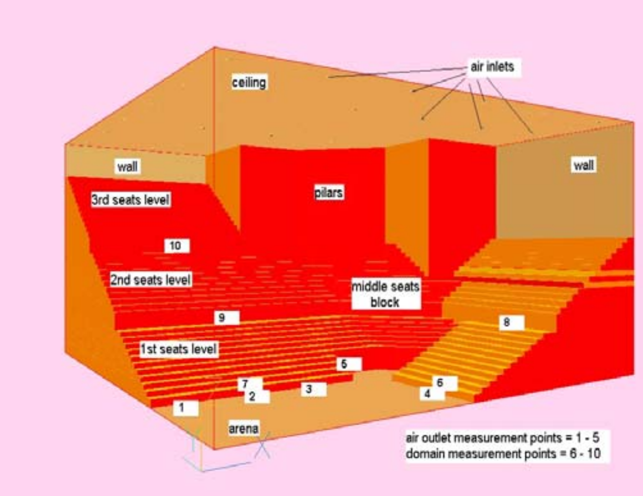

Figure 1: Geometrical domain – Basic

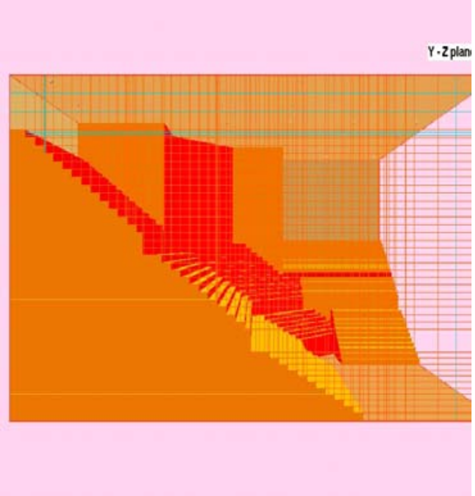

Figure 2: Grid view on Y–Z plane - Basic

The boundary and initial conditions are: (a) Fresh air comes in the hall via the ceiling circular fans (Figure 1), the diameters of which are either 0.4m or 0.63m and mean (axial along -z) velocities and turbulence intensities range from 1.18 to 3.38 m/s and 13 to 31 %, respectively, according to the experimental measurements. (b) The X – Z and Y – Z planes of the domain have symmetry boundary conditions (Figure 1). It is also important to note that many efforts were made to achieve the best balance among convergence, grid independency and saving of run-time due to the very complex domain geometry (Figure 2).

TABLE 1
Information and initialization data. The asterisk (*) corresponds to experimentally measured data.

DATA	BASIC	HEATING	COOLING
Grid cells	71x107x46	71x107x46	71x107x46
Min cell size (m)	0.63x0.42x0.48	0.63x0.42x0.48	0.63x0.42x0.48
Inlet air temp. (^{0}C)	*20.7 – 21.3	*28.8	20
Initial air temp. (^{0}C)	*20.2	*18.15	28
Ceiling surface temp. (^{0}C)	*22	*22	31
Floor surface temp. (^{0}C)	*19	*19	27
East wall surface temp. (^{0}C)	*20	*20	28
North wall surface temp. (^{0}C)	*20	*20	28
Pillars temp. (^{0}C)	*17 - 20	*17 - 20	29
1st seats level temp (^{0}C)	*18	*18	28
2nd seats level temp (^{0}C)	*18.5	*18.5	29
3rd seats level temp (^{0}C)	*19	*19	30

TABLE 2
Measured and computed velocities and temperatures at measurement points of the domain in Basic Case.

Measurement points of domain	V_{exp} (m/s)	V_{th} (m/s)	T_{exp} (^{0}C)	T_{th} (^{0}C)
1 (air-outlet)	0.43	0.34	21.8	19.3
2 (air-outlet)	0.41	0.20	21.3	19.3
3 (air-outlet)	0.31	0.21	21.5	19.3
4 (air-outlet)	0.19	0.32	21.6	19.3
5 (air-outlet)	0.42	0.25	21.6	19.4
6 (arena level)	0.09	0.06	20.2	20.7
7 (arena level)	0.12	0.10	19.9	20.8
8 (above 1st seats level)	0.20	0.20	20.2	20
9 (above 1st seats level)	0.23	0.02	20.4	19.3
10 (above 2nd seats level)	0.29	0.33	20.6	20.9

RESULTS AND DISCUSSION

(1) Basic Case: Computed results of Basic Case present good agreement with experimental results. Table 2 gives the measured and computed velocities (V_{exp} and V_{th}) and temperatures (T_{exp} and T_{th}) at several points of the domain including air-outlets and points at the arena and the seats levels. The disagreement observed for velocities at points 9 and 4 is attributed to the geometric complexity of those areas, which could not be modelled in detail. It is also observed that comparison between computed and measured temperatures at domain points 6 – 10 is better than at the points close to the air abductors of the HVAC system (air-outlets: 1 – 5). Since theoretical results are physically plausible, giving the highest temperatures at high levels and the lowest ones at low levels, the previous difference is attributed to ineffectiveness of the HVAC system in conjunction with certain modelling simplifications that had to be made for computational economy reasons. The airflow field formed in the hall is quite interesting. Figure 3 displays a vector plot of velocity on a Y-Z plane extending from a row of air-inlet fans at the ceiling. Air jets squirt from the ceiling air-inlets with maximum velocity 3.2m/s decreasing to 0.2 m/s at approximately 6.5m above the arena floor. Moving up from 1st seats level to 3rd seats level, jets become more intense with higher velocities reaching 0.9 – 1.3 m/s close to the spectators at the 3rd seats level and 1.5 m/s at the upper seats. Furthermore, large vortices are formed between air jets with air velocity being less than 0.2 m/s, which become more distinct above the seats.

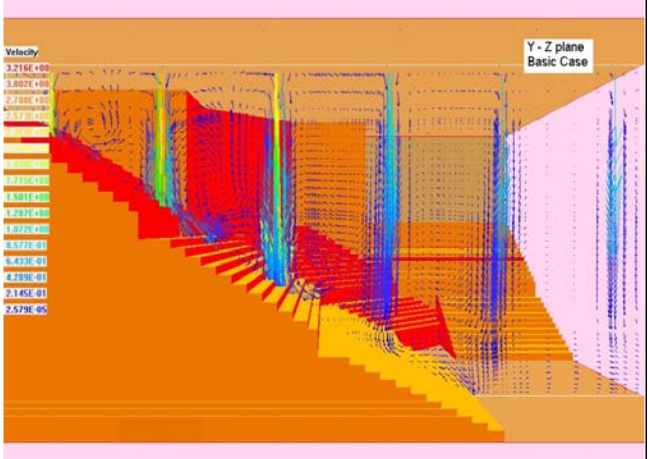

Figure 3: Air velocity field (m/s) – Basic

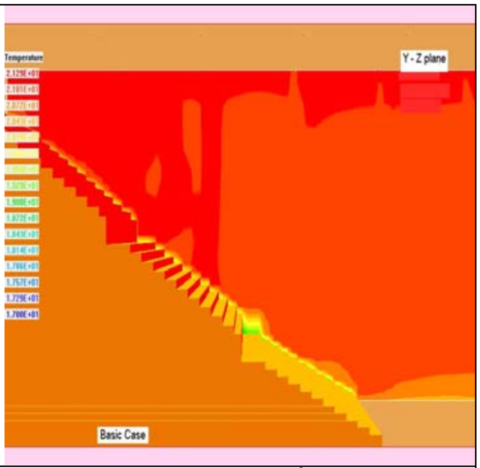

Figure 4: Temperature field (^{0}C) – Basic

Regarding the temperature field, a smooth stratification is formed in the hall ranging from 17 to 21^{0}C (Figure 4). The highest temperatures appear close to the ceiling and the upper seats, while the lowest ones are observed very close to the floor and the air-outlets. It is finally interesting to note that mean air velocity and temperature at the height of 2m above the arena where the athletes train and compete are 0.07 m/s (which is considered very low, according to ASHRAE standard) and 20.8^{0}C, respectively.

(2) Heating Case: This case corresponds to a certain experimental day for which measurements of air velocity and temperature are only available for point 2 – air outlet (Figure 1). Experimental results give 0.48 m/s and 20.2^{0}C for velocity and temperature, while computed results give 0.2 m/s and 21.37^{0}C, respectively. Regarding the air velocity (Figure 5) and temperature (Figure 6) fields prevailing in the hall, they are considerably altered with respect to those in the Basic Case. Temperature stratification is enhanced with values ranging from 17 to 29^{0}C (Figure 6). Warm air jets penetrate to a depth of about 7.5m above the arena and the 1st seats level, while they reach spectators at the upper seats. The highest temperatures

appear close to the ceiling around the jets and at the upper seats, exceeding 26^0C. Such temperatures are observed above the arena and the 1st seats level only at a height of over 10m. Furthermore, temperature decreases to 25^0C at about 0.8m from the floor and become even lower only very close to the surfaces and the air-outlets. It is finally interesting to note that mean air velocity and temperature at the height of 2m above the arena where the athletes train and compete are 0.05 m/s and 25.2^0C, respectively. Owing to the enhanced temperature stratification, air jets originating from the ceiling air inlet fans have smaller penetrating depths, compared to the Basic Case, reaching approximately 13m above the arena and the 1st seats level (Figure 5). Prevailing velocities appear very low (less than 0.05 m/s), whereas close to spectators at the 3rd seats level they increase to 0.8 - 1.5 m/s. Furthermore, vortices between air jets are of smaller scale and less intense with respect to the Basic Case, while they are maintained only at the higher levels close to the ceiling fans. Above the arena and the lower seats, a one-way direction flow is formed moving horizontally towards the centre of the hall. It is also interesting to note that mean air velocity and temperature at the height of 2m above the arena where the athletes train and compete are 0.05 m/s and 25.2^0C, respectively.

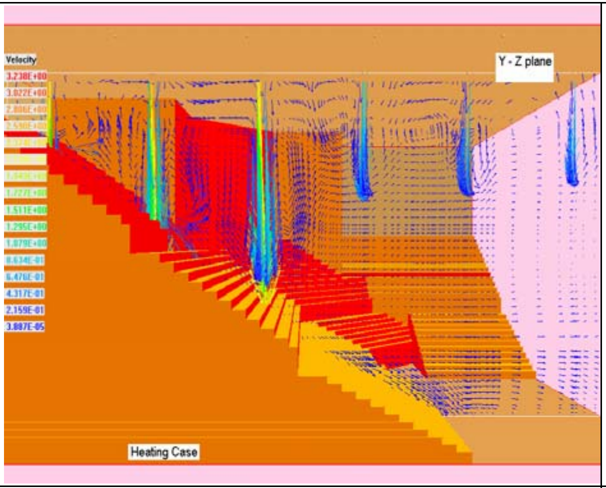

Figure 5: Air velocity field (m/s) – Heating Case

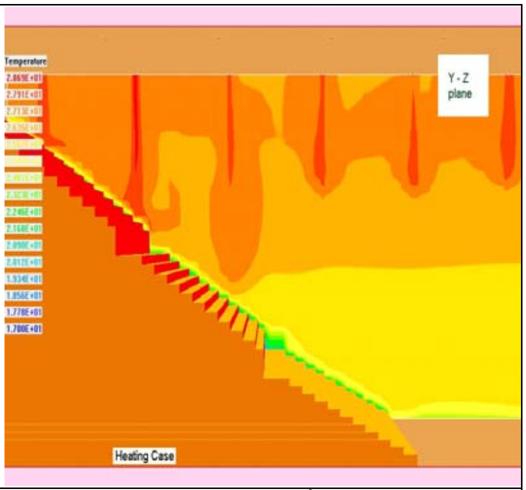

Figure 6: Temperature field (^{0}C) – Heating Case

(3) Cooling Case: A typical summer day is considered in this case with outdoor temperature exceeding 30^0C, according to meteorological data for the experimental site. Boundary and initial conditions are given in Table 1. The air velocity and temperature fields prevailing in the hall under cooling conditions are illustrated in Figures 7 and 8, respectively. Velocity fields are not significantly changed compared with the Basic Case. Air jets have smaller penetrating depths and velocities decrease to 0.2 m/s at approximately 9m from the floor (Figure 7). Going up the seats jets become more intense with velocities slightly increasing to 0.4 m/s close to spectators at the 2nd seats level and further increasing to 0.9 - 1.6 m/s at the upper seats. Large vortices are formed between the jets with low velocities prevailing therein (0.2 – 0.3 m/s). However, air flow above the arena and the 1st seats level until a height of 5m seems one-way directional moving from the arena to the seats. Regarding temperature, considerable stratification is formed in the hall (Figure 8) with the lowest values (20 – 23^0C) being observed very close to the air jets originating from the ceiling inlets, at the area between the 2nd and 3rd seats level until a height of 2m from the spectators' seats as well as at the right hand 1st block of seats. Temperature exceeds 24^0C at a height of approximately 18m above the arena reaching 25^0C very close to the ceiling, while at the rest of the indoor space temperature slightly fluctuates over 24^0C. It is finally interesting to note that mean air velocity and temperature at the height of 2m above the arena where the athletes train and compete are 0.06 m/s and 23.4^0C, respectively.

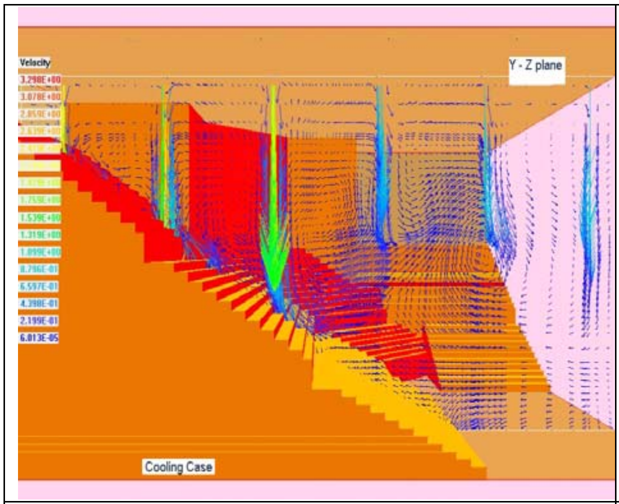

Figure 7: Air velocity field (m/s) – Cooling Case

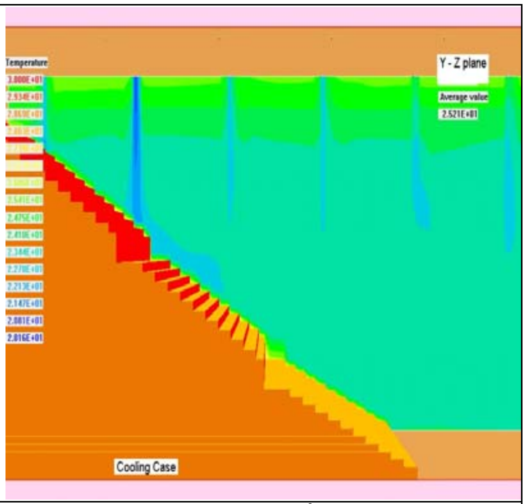

Figure 8: Temperature field (^{0}C) – Cooling Case

CONCLUSIONS

Comparison between experimental and computed results was satisfactory with only discrepancy observed being attributed to simplifications of the model setup for computational economy reasons. Airflow fields were characterised by large distinct vortices extending from top to bottom between air jets originating from the ceiling air inlet fans. Velocities were higher at the upper spectators' seats and temperature depicted a smooth stratification, which was enhanced under heating ventilation conditions. When heating was applied air jets had considerably smaller penetrating depths, vortices were less intense, velocities slightly decreased, while airflow field above the arena turned to one-way horizontal flow. This was also observed under cooling ventilation conditions, whilst overall less significant changes were imposed to the airflow and temperature patterns. Air jets and velocities became slightly smaller compared with the Basic Case (air-conditioning HVAC operation) and temperature stratification was more intense. Further work includes scenarios of different uses of hall and consideration of pollutants. For example, an "athletic event" day has been studied with the hall occupied by spectators and indoor pollutant sources considered as well as infiltration of outdoor originating pollutants. Furthermore, scenarios of different uses of hall under different ventilation conditions and presence of pollution sources including more physical processes are under study.

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