Numerical Investigation of Flow Patterns and Thermal Comfort in Air-Conditioned Lecture Rooms

Taher M. Abou-deif, Mahmoud A. Fouad, and Essam E. Khalil

***Abstract*—**The present paper was concerned primarily with the analysis, simulation of the air flow and thermal patterns in a lecture room. The paper is devoted to numerically investigate the influence of location and number of ventilation and air conditioning supply and extracts openings on air flow properties in a lecture room. The work focuses on air flow patterns, thermal behaviour in lecture room where large number of students. The effectiveness of an air flow system is commonly assessed by the successful removal of sensible and latent loads from occupants with additional of attaining air pollutant at a prescribed level to attain the human thermal comfort conditions and to improve the indoor air quality; this is the main target during the present paper. The study is carried out using computational fluid dynamics (CFD) simulation techniques as embedded in the commercially available CFD code (FLUENT 6.2). The CFD modelling techniques solved the continuity, momentum and energy conservation equations in addition to standard $k-\varepsilon$ model equations for turbulence closure.

Throughout the investigations, numerical validation is carried out by way of comparisons of numerical and experimental results. Good agreement is found among both predictions.

***Keywords*—**Air Conditioning, CFD, Lecture Rooms, Thermal Comfort

I. Introduction

THE present work focuses on air flow patterns, thermal behaviours in air-conditioned lecture room. That is in order to satisfy the student's thermal comfort conditions and improving the indoor air quality, which are the main targets during this work. Air conditioning term can be defined as a process that controls the microclimate of an enclosed space. This process involves the movement of air through a space that has certain characteristics of temperature, humidity, cleanliness, pressure differential and noise level attenuation in order to satisfying a comfortable and healthy environment for the occupants.

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A. Thermal Comfort

Thermal comfort is a condition of mind which expresses satisfaction with the surrounding environment, most important factors influencing thermal comfort are.

Environmental factors:

- Air temperature, air speed, relative humidity, air quality, and Noise.

Other factors:

- Activity level, clothing level, and psychological factors: such as mental effort.

Achieving thermal comfort for most occupants of buildings or other enclosures is a main goal of HVAC design engineers.

B. In-Door Air Quality

Indoor Air Quality (IAQ) deals with the content of interior air that could affect health and comfort of building occupants. The IAQ may be compromised by microbial contaminants (mold, bacteria), chemicals (such as carbon dioxide, radon), allergens, or any mass or energy stressor that can induce health effects. So, using ventilation to dilute contaminants and improve the indoor air quality in most buildings. Carbon is an indoor pollutants emitted by humans and correlates with human metabolic activity. Carbon dioxide concentration at levels that are unusually high indoors may cause occupants to grow drowsy, get headaches, or function at lower activity levels, etc. Table I is a listing of carbon dioxide air concentrations and related health effects and standards.

TABLE I
Carbon Dioxide Air Concentration Level Standards

Carbon Dioxide Level	Health Effects	Standards or Use of Concentration	Reference
600 ppm	None	Most indoor air complaints eliminated, used as reference for air exchange for protection of children.	NIOSH [1]
800 ppm	None	Used as an indicator of ventilation inadequacy in schools and public buildings, used as reference for air exchange for protection of children.	MDPH [2]
1000 ppm	None	Used as an indicator of ventilation inadequacy concerning removal of odors from the interior of building.	ASHRAE [3]

5000 ppm	No acute (short term) or chronic (long-term) health effects	Permissible Exposure Limit (8-hour workday) / Threshold Limit Value.	ACGIH [4], OSHA [5]

C. Ventilation Principles

Ventilation is the exchange of air, typically between an indoor space and the outside. When people are present, ventilation is especially necessary to evacuate the carbon dioxide produced and renew the oxygen used up. It is also needed to remove other pollutants (smoke, chemicals, etc.) from the space. Ventilation air may be classified into natural or mechanical ventilation. In natural ventilation or gravity ventilation, uses the natural forces caused by the temperature difference inside the space to induce air circulation and removal.

D. Air Exchange Rate

The most common method to measure the ventilation rate is the air exchange rate; the air exchange rate has units of 1/time. When the time unit is hours, the air exchange rate is also called air changes per hour (ACH). The rate of ACH determines the rate at which the total volume of air in the room is cleaned by an air purification system, which is a major factor in the degree of air cleaning that can be achieved. Where it is the total volume of air flowing into a space in 1 hour divided by the volume of the space, then ACH can be expressed mathematically as,

$$ACH = 3600\, Q / V \tag{1}$$

where: Q = volumetric air flow rate through the room, m^3/s,
V = volume of the room, m^3

The air exchange rate may be defined for several different situations. For example, the air exchange rate for an entire space served by an air handling unit compares the amount of outside air brought into the space to the total interior volume, this the nominal air exchange rate.

E. Air Conditioning Systems

Air conditioning systems can be categorized according to the means by which the controllable cooling/heating is accomplished in the conditioned space. There are four basic systems categories:-

1. All-Air Systems; air is used to carry the energy from indoor to outdoor and vice versa.
2. All-Water Systems; water is used to carry the energy from indoor to outdoor and vice versa,
3. Air-Water Systems; air and water are used to carry the energy from indoor to outdoor and vice versa.
4. In Direct Expansion (DX) Systems; refrigerant is used to carry the energy from indoor to outdoor or vice versa [i.e. direct expansion of refrigerant, without the chilled water cooling medium].

II. Assessment and Validation

An experimental investigation on a real air-conditioned lecture room was done. This investigation aims to validate the used computational fluid dynamics code, the results from both investigations, experimental and numerical, will be compared. Flow parameters like velocity and temperature have been measured at relatively important places on a plane perpendicular to a grill in the supply duct. The space configuration and the measuring instruments used are described. In addition, the experimental locations are described in details. Furthermore, the experimental procedure and test precautions are discussed briefly.

A. Description of the Lecture Room Configuration

Room Geometry

The room under investigation is a real lecture room "dissuasion room at building number 17" Faculty of Engineering, Cairo University, which has main dimensions as shown in the following Fig. 1. Conditioned air is supplied to the room through four air conditioners with outside dimensions as shown in Fig. 2.

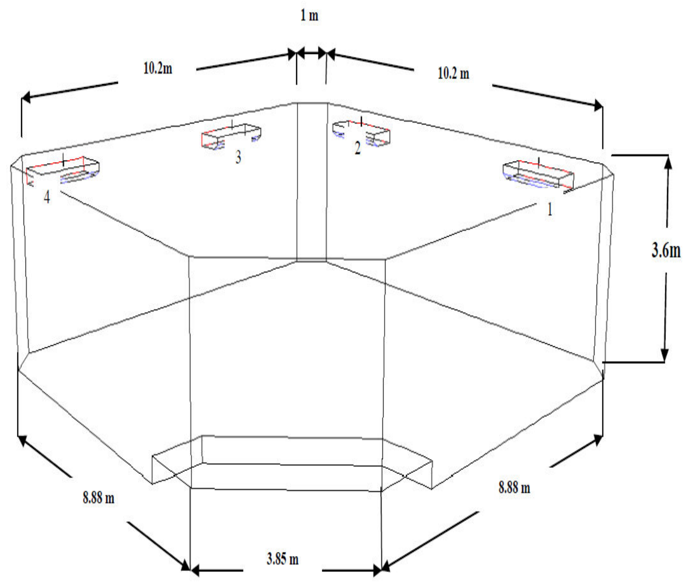

Fig. 1 Lecture room configuration

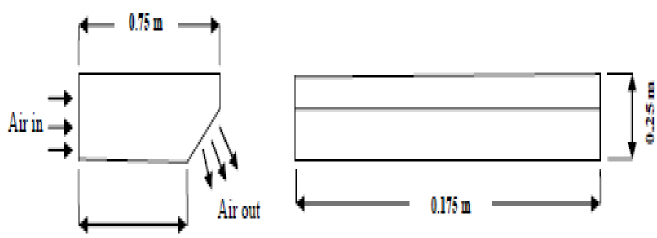

Fig. 2 Air conditioner configuration

B. Measuring Locations

One place was chosen to perform measurements a plane passing with a supply grill. A vertical plane perpendicular to the supply grill of air conditioner number 3 to show the decay in inlet air velocity and temperature variation downstream. This plane was taken to pass with a supply grill of air conditioner number 3. Measuring points is selected at each 20 cm on this plane. Temperature and velocity are measured at 110 points in this plane. The layout of these measuring points is shown in Fig. 3.

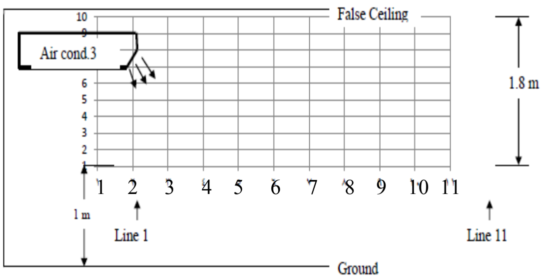

Fig. 3 (a) Lines of measurements near supply grill

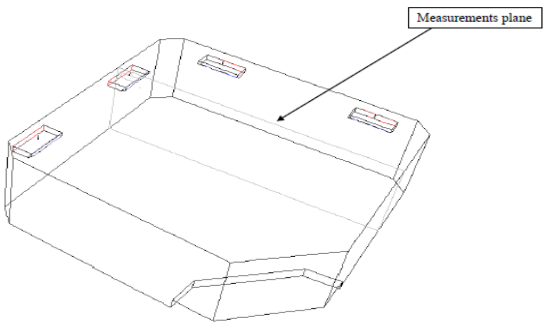

Fig. 3 (b) Configuration of measurements plane

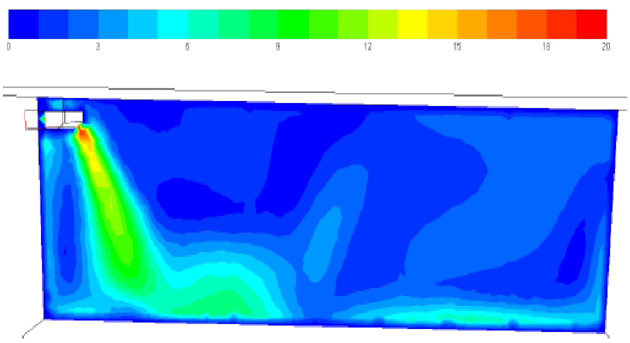

Fig. 3 (c) Predicted velocity contours in the measurements plane

TABLE II
MEASUREMENTS LINES COORDINATES AT SUPPLY GRILL

No.	X (m)	Y (m)		Z (m)
		From	To	
1	0.25	1	2.8	-11.5
2	0.4	1	2.8	-11.4
3	0.55	1	2.8	-11.3
4	0.65	1	2.8	-11.2
5	0.8	1	2.8	-11.1
6	0.95	1	2.8	-10.9
7	1.05	1	2.8	-10.75
8	1.2	1	2.8	-10.6
9	1.4	1	2.8	-10.45
10	1.5	1	2.8	-10.3
11	1.75	1	2.8	-10

C. Assessment of CFD Modeling Validation

The typical validation procedure in CFD, as well as other fields, involves graphical comparisons of computational results and the corresponding available experimental data. If the computational results "generally agree" with the experimental data, the computational results are declared "validated".

D. Results and Discussion

Temperature and mean velocity values downstream the supply duct is compared below.

1. Temperature Measurements

Fig. 4 shows comparisons between measured and predicted air temperature profiles downstream the supply grill at line 5.

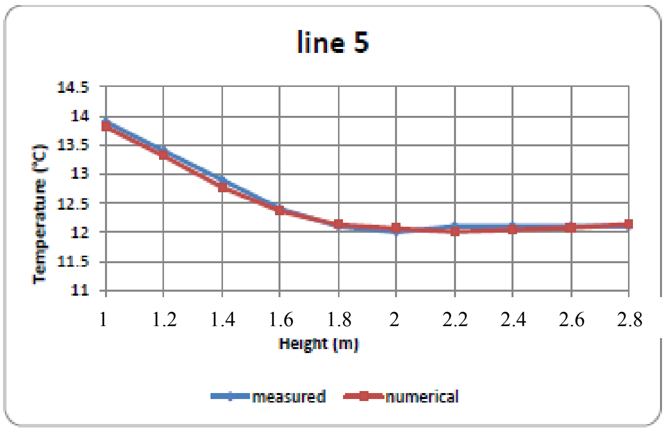

Fig. 4 Comparisons between measured and predicted air temperature profiles downstream the supply grill at line 5

The assumptions were suggested in the numerical model to represent the air supply grill, gave a good agreement with the measured results. The measured values are not equal the numerical ones due to the limited measuring instrument resolution.

2. Velocity Measurements

Fig. 5 shows comparisons between measured and predicted air velocity downstream the supply grill at line 5.

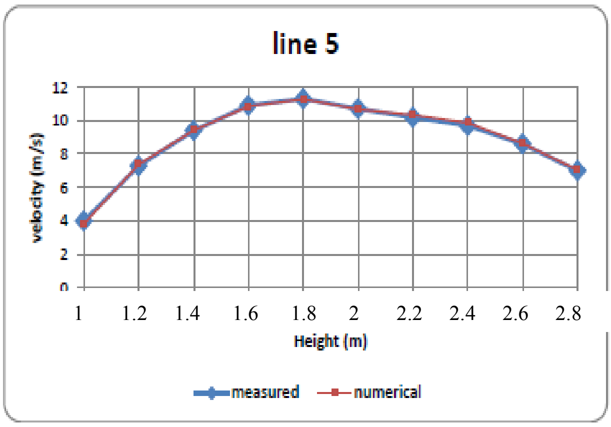

Fig. 5 Comparisons between measured and predicted air velocity downstream the supply grill at line 5

E. Conclusions

The measured air temperatures and velocities were compared against the predicted results. Fair agreement can be found between the simulated and measured results. For the measuring points, the average velocity and temperature prediction errors were calculated equal to 0.04 m/s and 0.5 °C (1.8%), respectively. These values verify the satisfactory performance of the CFD model, taking into account the accuracy of the measurement. And most of the predicted air temperatures and velocities were overestimated. Generally the calculations yielded the same trends as the measurements. Curves of measured temperature is displaced from the predicted ones, this could be due to errors in specifying the boundary conditions. All comparisons carried out and shown in this validation gave a direct conclusion of the numerical model capability to predict the air flow characteristics within acceptable deviation from the measured values.

III. Results and Discussions

A. Case Studies Specifications

All of the case studies will be developed with utilizing FLUENT 6.2 and GAMBIT 2.2 (as mentioned before) based on a lecture room configuration with 12 ×6 × 4 m (12 m in length (L), 6 m in width (W), and 4 m in height (H)).
Three case studies developed as shown in figure 6, 7, and 8 to show the influence of supply-extract positions on the air flow characteristics.

Case 1 describes the air flow characteristics at ceiling air supply with 6 square supply air ports distributed uniformly at the ceiling, while 6 extract ports from all side walls. Case 2 describes the air flow characteristics when the air supply ports from the side wall (wall of X-Z plane at X = 6 m, five ports), while the extractions from the opposite wall (wall of X-Z plane at X = 0 m, five ports).

Case 3 describes the air flow characteristics at ceiling air supply with 6 square supply air ports distributed uniformly at the ceiling, while 6 square extract ports at ceiling also

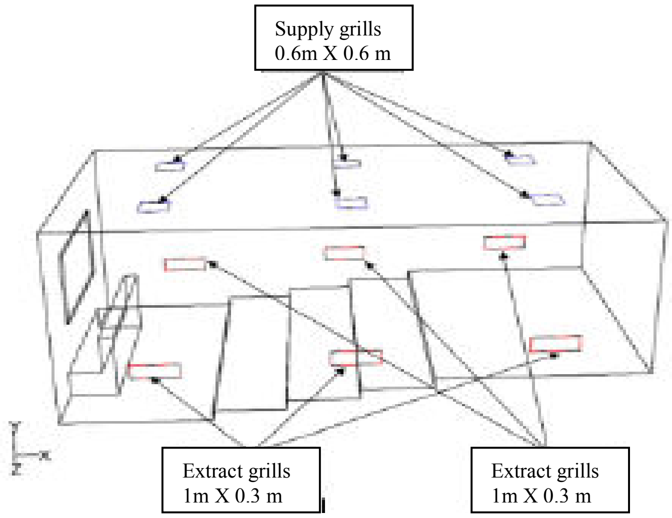

Fig. 6 Case 1 Configuration

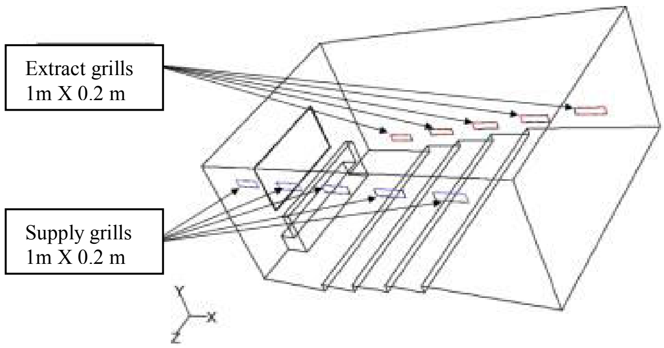

Fig. 7 Case 1 Configuration

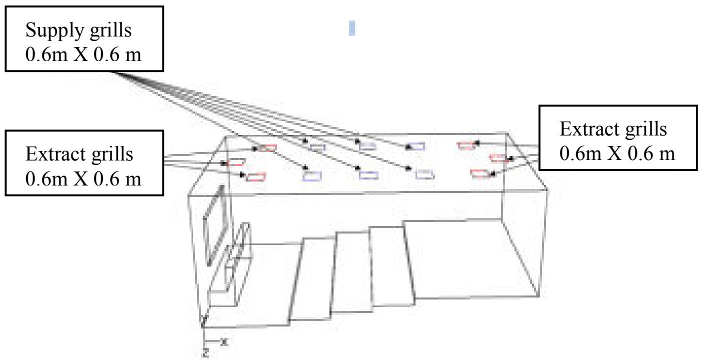

Fig. 8 Case 3 Configuration

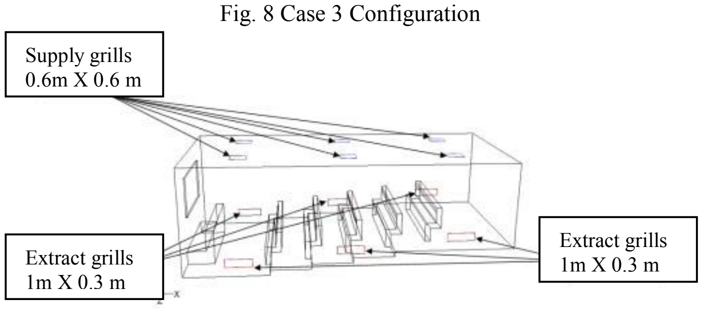

Fig. 9 Modeling of case 1 with effect of students load

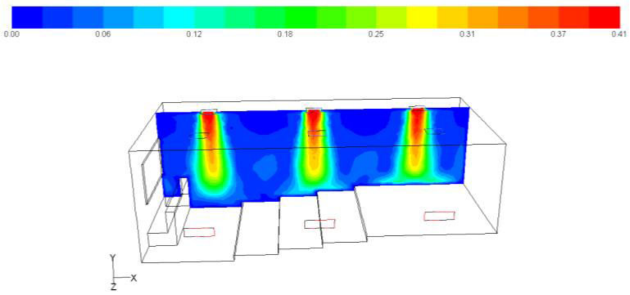

Fig. 10 (Case 1) Velocity magnitude contours (m/s),

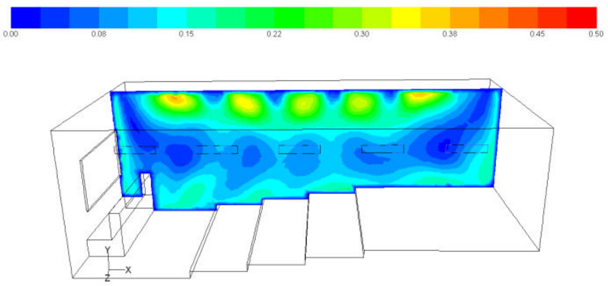

Fig. 11 (Case 2) Velocity magnitude contours (m/s), Vertical plane at Z=1.5 m

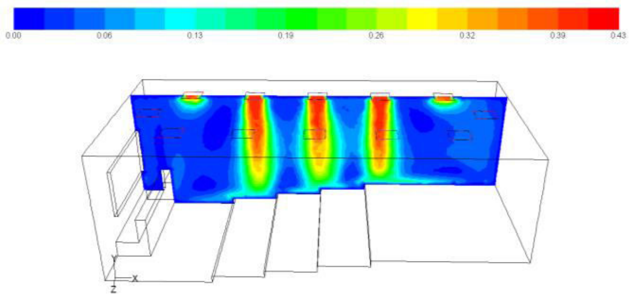

Fig. 12 (Case 3) Velocity magnitude contours (m/s), vertical plane at Z=1.5 m

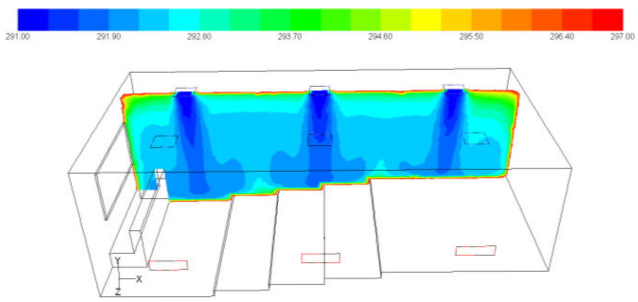

Fig. 13 (Case 1) Temperature contours (K), Vertical plane at Z=1.5 m

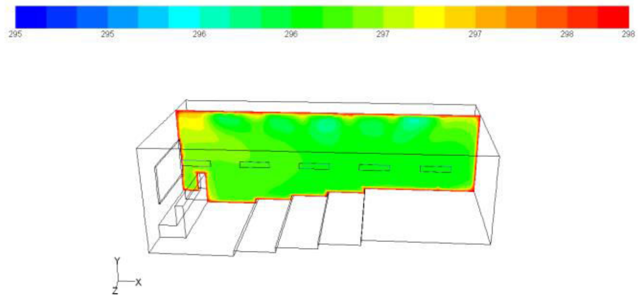

Fig. 14 (Case 2) Temperature contours (K), vertical plane at Z=1.5 m

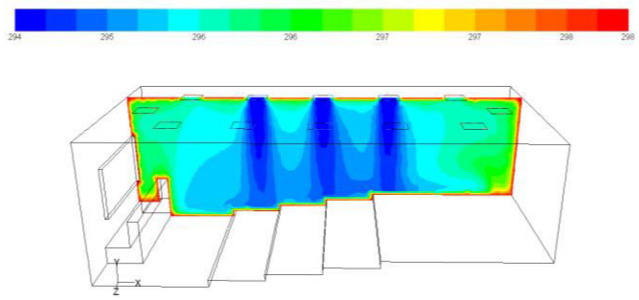

Fig. 15 (Case 3) Temperature contours (K), vertical plane at Z=1.5 m

A complete air flow properties prediction of case 1 in actual study (student's presence); will lead us to more actually comparison with standard values in order to give a comfortable environment within the occupied zones.

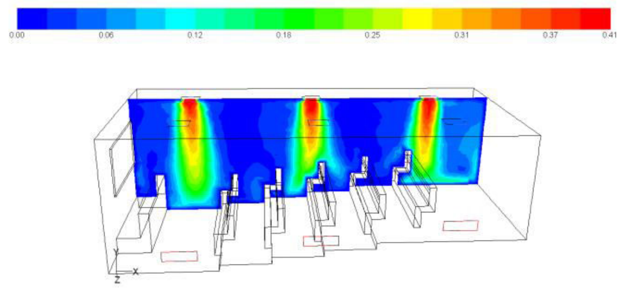

Fig. 16 (Case 1) Velocity magnitude contours (m/s), vertical plane at Z=1.5 m

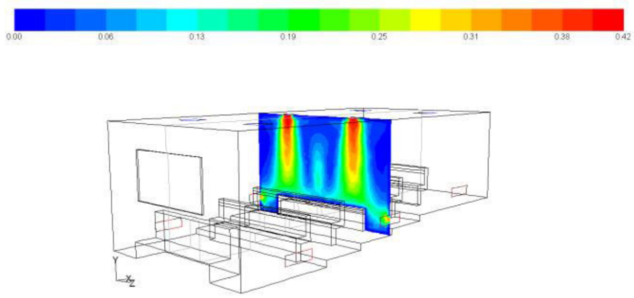

Fig. 17 (Case 1) Velocity magnitude contours (m/s), Vertical plane at X=6 m

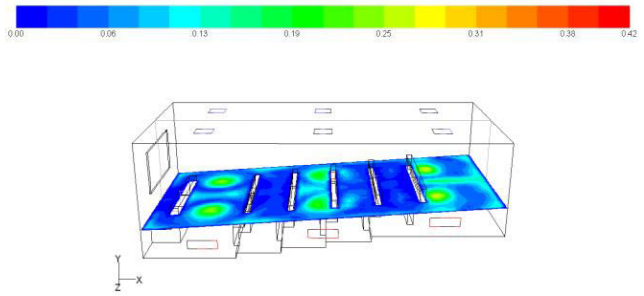

Fig. 18 (Case 1) Temperature contours (K), horizontal plane at Y=1m

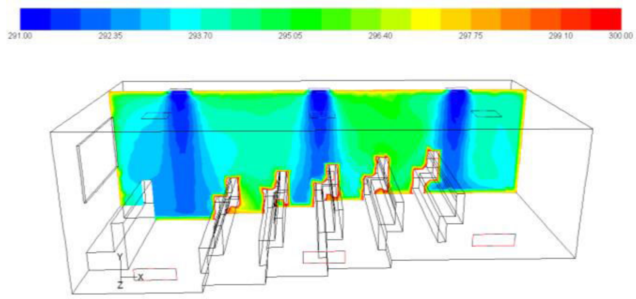

Fig. 19 (Case 1) Temperature contours (K), vertical plane at Z=1.5 m

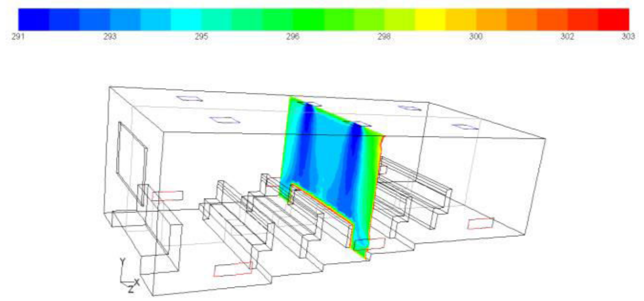

Fig. 20 (Case 1) Temperature contours (K), vertical plane at X=6 m

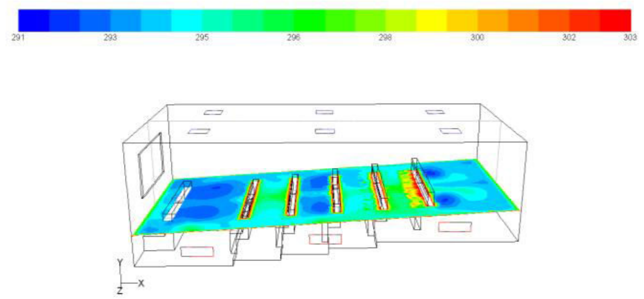

Fig. 21 (Case 1) Temperature contours (K), Horizontal plane at Y=1m

Figures from 10 to 12 shows the velocity contours in m/s for cases 1, 2, and 3 respectively at vertical plane at Z = 1.5 m. Figures from 13 to 15 shows the temperature contours in K for cases 1, 2, and 3 respectively at vertical plane at Z = 1.5 m. Fig. 16 shows the velocity contours in m/s for case 1 with the effect of student's presence at vertical plane at Z = 1.5 m. Fig. 17 shows the velocity contours in m/s for case 1 with the effect of student's presence at vertical plane at X = 6 m. Fig. 18 shows the velocity contours in m/s for case 1 with the effect of student's presence at horizontal plane at Y = 1 m. Fig. 19 shows the temperature contours in k for case 1 with the effect of student's presence at vertical plane at Z = 1.5 m. Fig. 20 shows the temperature contours in k for case 1 with the effect of student's presence at vertical plane at X = 6 m. Fig. 21 shows the temperature contours in k for case 1 with the effect of student's presence at vertical plane at Y = 1 m.

IV. Concluding Remarks

From the previous chapters and according to the results obtained using the numerical investigation, the following conclusions can expressed concerning different lecture room configurations:

- Cases 2 and 3 are rejected due to their problems of stratification and uncomfortable conditions.
- CO2 concentrations and relative humidity magnitudes developed in the present work may be slightly decreased due to modeling of students presence in the room based on the maximum full load design through assumption of no free spaces between audience bodies, which in the same chair rows.
- Total fresh air through air supply ports assumed in cases of students presence effect, but in actual mixing between recirculated and fresh air should be designed in order to minimize the total cost of this design.
- Increasing number of air extraction ports will lead to more uniform air flow distribution and minimize the stagnant air zones.

References

[1] NIOSH, "Guidance for Indoor Air Quality Investigations ", National Institute for Occupational Safety and Health, Hazards Evaluations and Technical Assistance Branch, Division of Surveillance, Hazard Evaluation and Field Studies Cincinnati, OH, 1987.

[2] MDPH, " Indoor Air Quality Assessment ", Massachusetts Department of Public Health, Bureau of Environmental Health Assessment, Boston, MA, 2000.

[3] ASHRAE, " ASHRAE Standard 62-2004: ventilation for acceptable indoor air quality ", American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, USA, 2004.

[4] ACGIH, "Guide to Occupational Exposures-1999 ", American Conference of Governmental Industrial Hygienists, Cincinnati, OH, 1999.

[5] OSHA, "Limits for Air Contaminants ", Occupational Safety and Health Administration, Code of Federal Regulations, 29 C.F.R. 1910.1000 Table Z-1-A, 1997.