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Numerical Study of IAQ in Schools

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1. Abstract

Good indoor air quality (IAQ) in schools contributes to a favourable learning environment for students, productivity for teachers and stuff, and well being for school occupants. These combine to assist a school in its core mission, educating children. Poor IAQ in schools can result in decreased academic performance and days lost due to illness in the school age population. The present study investigates the air movement and contaminants concentrations in a typical Egyptian school classroom both numerically and experimentally.

A 3-D numerical model was built using a CFD code in order to investigate the effect of the air flow patterns on the contaminant concentration distribution with turbulent flow. The code uses the finite volume method as a numerical technique in solving the fluid flow governing equations.

Exhaust ventilation system configurations were suggested to evaluate the distributions of the contaminant concentrations as a major parameter affecting the IAQ. The results showed that the natural ventilation cannot be considered as an effective method for proper ventilation, therefore mechanical ventilation is important to remove the contaminant more efficiently and to maintain the IAQ standards.

2. Introduction

Indoor air quality is an important component of a healthy indoor environment. Proper IAQ may help schools achieve their primary goal of educating their students well. The school population is comprised of a wide variety of people who react differently to various pollutants in the air, Thomson (1998). Complicating factors include allergies, asthma, respiratory disease, and suppressed immune systems.

Children comprise the majority of the school population. Their developing immune and respiratory systems and the amount of air they breathe relative to the amount adults breathe makes them especially susceptible to air pollution.

The purpose of this investigation is to study the air movement and pollutants distribution numerically in a typical class room. A numerical model has been developed for a physical system as an original case to simulate the air flow pattern and concentration distribution for a three-dimensional, incompressible, turbulent flow of a class room with controlled forced ventilation system. A 3-D analysis using finite volume CFD program has been developed to predict the air flow pattern and contaminants concentration inside the student’s class room.

3. FLUID FLOW GOVERNING EQUATIONS

The Navier-Stokes, continuity equations and energy equations are the fundamental equations describing the fluid flow problem. These governing equations are expressed in terms of Partial Differential Equations (PDE's). These PDE's are discretized using the finite volume techniques.
the general form of the momentum, energy, species, and turbulent model equations, to facilitate the discretization, is the following scalar transport equation:

$$\frac{\partial \rho \phi}{\partial t}+\frac{\partial \rho U \phi}{\partial x}+\frac{\partial \rho V \phi}{\partial y}+\frac{\partial \rho W \phi}{\partial z}=\frac{\partial}{\partial x}\left(\Gamma_{\phi}\frac{\partial \phi}{\partial x}\right)+\frac{\partial}{\partial y}\left(\Gamma_{\phi}\frac{\partial \phi}{\partial y}\right)+\frac{\partial}{\partial z}\left(\Gamma_{\phi}\frac{\partial \phi}{\partial z}\right)+S_{\phi}\ldots 1$$

where φ : dependant variable (U, V, W, T, k, ε)
S_{φ} : source term
Γ_{φ} : Diffusion coefficient

The CFD code used in the present paper solves the transport equations of 3-D thermal incompressible turbulent flow in the Cartesian Coordinates. The k-ε model is a two-equation turbulent model, where two turbulent transport equations are solved to obtain the evolution of the turbulence.

The numerical mesh for the created volume was generated using mesh generator program. The volume is meshed using the tetrahedral finite volume mesh with a mesh interval of 0.15. The total number of nodes in space volume grid was 23517 nodes.

Discretization is the process by which the partial differential equations are transformed into algebraic equations with the aid of assumptions on the spatial distribution of flow and fluid properties. In the present work, the p.d.e's are discretized and transformed to finite-difference equations (algebraic f.d.e's). Discretization is based on the "control - volume approach". This means the partial differential equations are formally integrated over a small control volume of the solution domain, which is covered by a numerical mesh. It should be noted that this approach leads to a solving scheme which retains the conservative properties of the governing p.d.e's.

Using the segregated solver in the solution algorithm, the governing equations are solved sequentially. To obtain a converged solution, several iterations of the solution loop must be performed. In the segregated solution method, each discrete governing equation is linearized implicitly with respect to that equation's dependent variable. This will result in a system of linear equations for each cell in the domain.

4. The Simulation Model

A classroom in a school was chosen as a physical model for the present research, which will be referred to as original case. The natural ventilation system of the original case under investigation will be modeled as the starting point of research. The original case classroom has two side by side windows and a door, having a dimensions of (5.7, 2.7, 6.9) m in the Cartesian Coordinates (x, y, z) respectively as shown in figure (1).

The student's bodies are treated as obstacles its walls having a temperature of 37 ºC Guyton (1986) and heat generation rate of 850 w/m^3 per student. The heat generation of the bodies is calculated according to the metabolic rate. The faces of the students are treated as a species source due to the presence of the CO_2 in the expired air of the respiratory system of the students. The volume of 0.5 liters is considered as the volume of an average breath per student Schottelius (1978), and the volume of the gases in dry expired air under standard conditions are: 74.5 % N_2, 15.7 % O_2, 3.6 % CO_2 and 6.2 % H_2O, Guyton (1986). The mass flow or expired air from the students is calculated as $1.933*10^{-4}$ kg/s per student based on 20 times per minute Schottelius (1978), during normal activity of the age of less than 15 years.

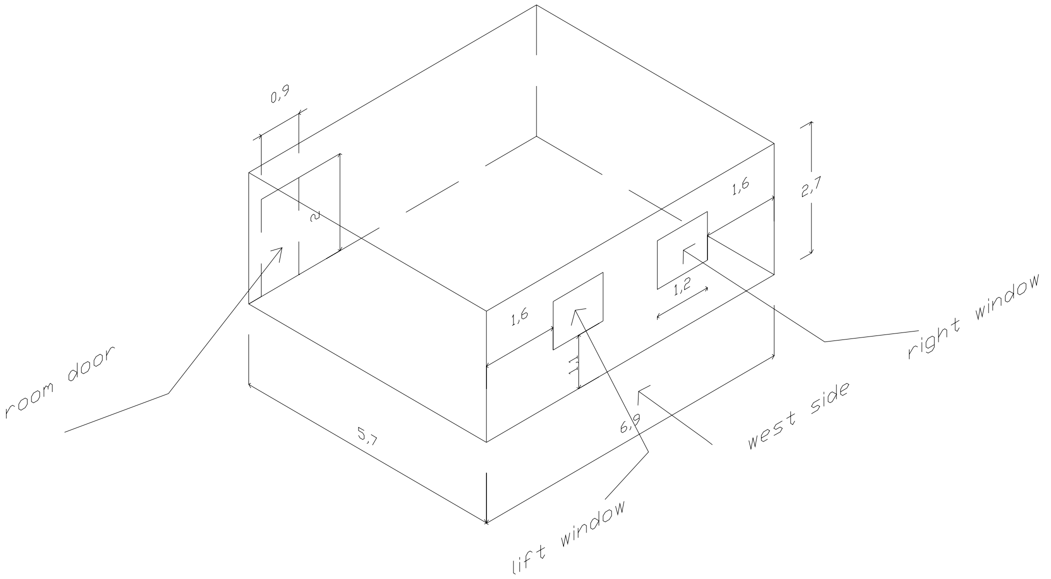

Figure (1) schematic diagram of the original case classroom

Different mechanical ventilation system configurations are suggested. Four general exhaust ventilation system configurations are proposed to modify the original case IAQ parameters and the contaminant concentration distribution:

Proposed configuration (1): uses one exhaust fan at the center of west side of the case study classroom at a height of 2 m from the ground level. The supply air will be though two louvers installed at the two windows as seen in figure (2) a.

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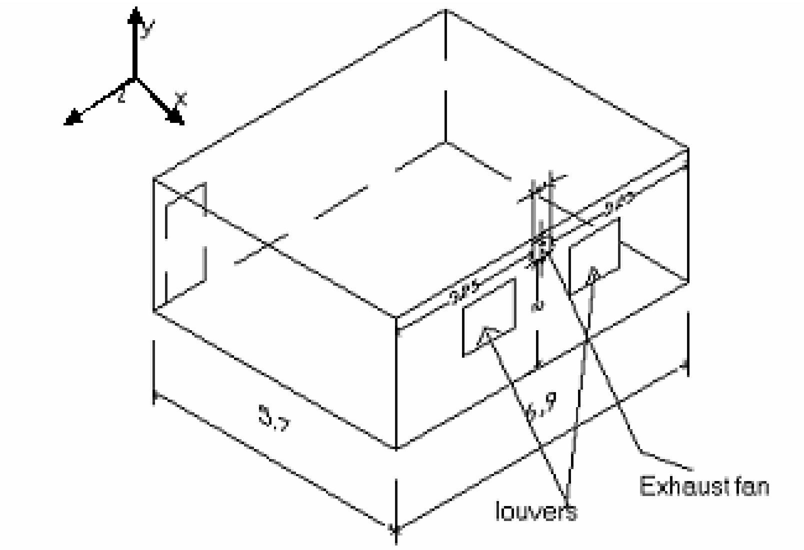
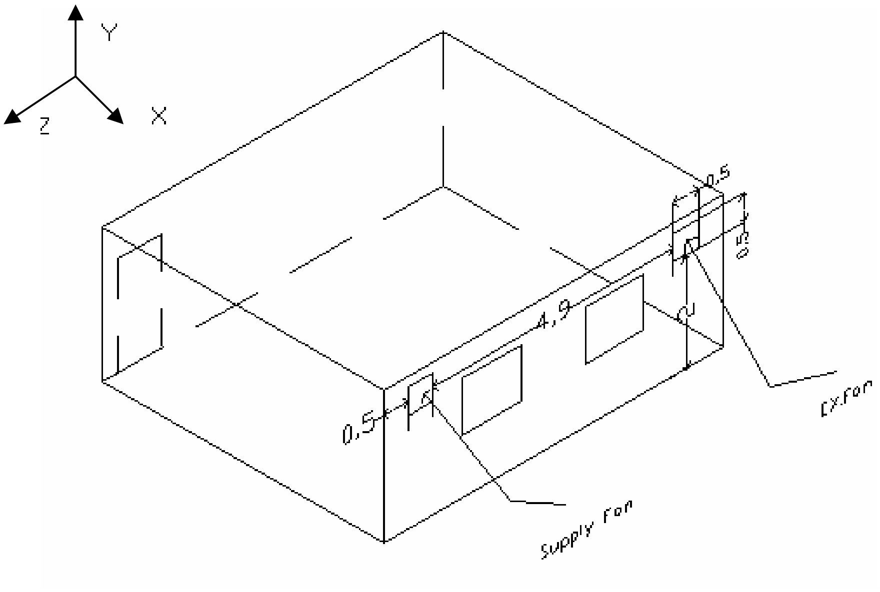
Proposed configuration (2): this mechanical ventilation system includes one wall mounted axial exhaust fan and one wall mounted axial supply fan mounted in the west side of the case study classroom at a level of 2m from the floor as seen in figure (2) b.

Proposed configuration (3): the third mechanical ventilation system configuration using centrifugal wall mounted supply fan distribute the air into the classroom by duct system through four 10"*10" supply ceiling diffusers with 125 cfm each, and centrifugal wall mounted exhaust fan collect the exhausted air through 3*1.5 m two slots 450 cfm exhaust grille as seen in figure (2) c.

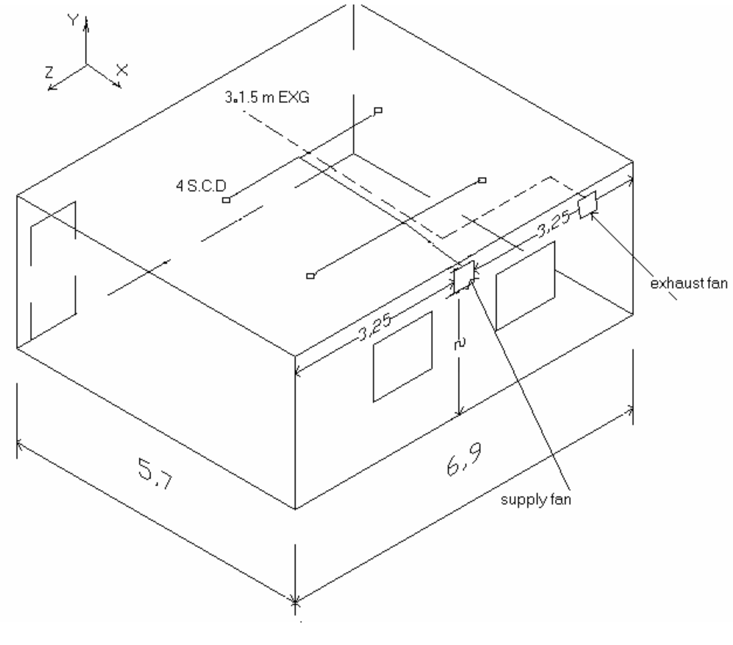
Proposed configuration (4): the fourth general exhaust ventilation system configuration is the same as configuration (3) but using two 3*1.5 m one slot exhaust grills instead of one as seen in figure (2) d.



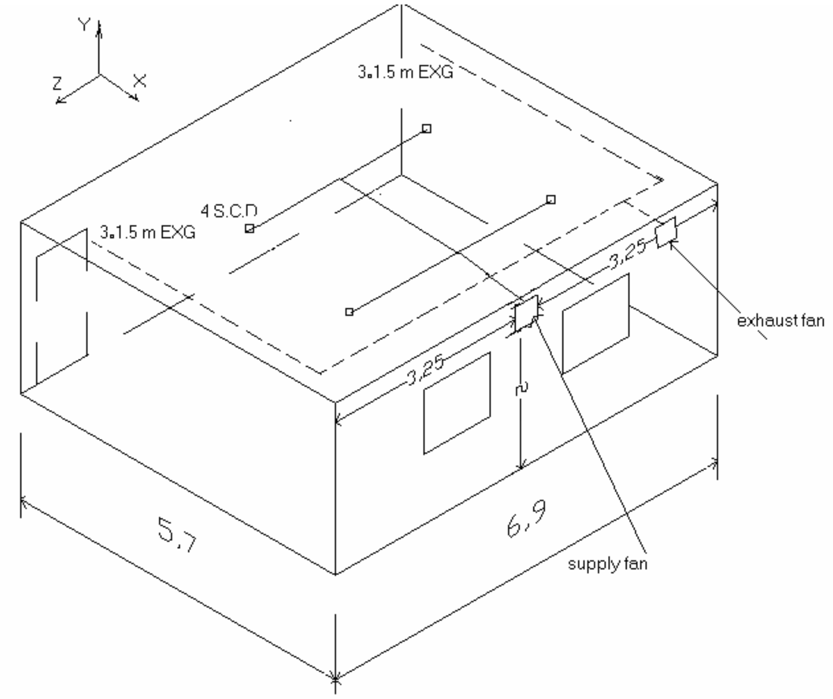
(a) Configuration 1



(b) Configuration 2



(c) Configuration 3



(d) Configuration 4

Figure (2), schematic diagram of the four general exhaust ventilation system configurations.

5. Minimum Physiological Requirements Based on CO_2 Concentration

The rate at which oxygen is consumed and carbon dioxide is generated depends on physical activity. A simple mass balance equation gives the outdoor air flow rate needed to maintain the steady state CO_2 concentration below or equal the standard limit.

$V_O = G / (C_S - C_O)$ ……………………… 2

Where:

V_O =outdoor air flow rate per person.

G = CO_2 generation rate per person.

C_S = CO_2 concentration in the space.

C_O = CO_2 concentration in outdoor air.

At an activity level of 70 w/m^2 or 1.2 met (1.0 met=18.4 Btu/hr.ft^2 or 5.387 w/m^2) corresponding to sedentary activity, the CO_2 generation rate is 0.31 L/min (ASHRAE 62.1-2004).

Laboratory and field studies have shown that with sedentary person about 7.5 L/s (15 cfm) per person of outdoor air will dilute odours from human bioeffluents to levels that is satisfy a substantial majority (80 %) of unadapted persons (visitors) to a space (Berg-Munch at al. 1986; Cain et al. 1983; Fanger and Berg-Munch 1983; Iwashita et al. 1989; Yaglou et al. 1936).

The ventilation rate of 7.5 L/s (15 cfm) per person is resulting from CO_2 concentration difference between outdoor and indoor of:

$C_S - C_O = G / V_O$

$= 0.31/(7.5*60)$

=0.000689 litre of CO_2 per litre of air

=700 PPM

This means that the 7.5 L/s (15 cfm) per person is based on 300 PPM CO_2 concentration in outdoor air if we targeted to maintain 1000 PPM CO_2 concentration in the space.
But unfortunately we can not apply 300 PPM CO_2 concentration in outdoor for every where. CO_2 concentration in outdoor has to be measured before considering 15 cfm per person because it varies from place to another.

For example, if we apply 15 cfm per person in a place located in a city with outdoor CO_2 concentration of 500 PPM, the resulting indoor CO_2 concentration will be 1200 PPM while the correct ventilation rate according to equation (2) is 21.2 cfm per person are required in order to avoid discomfort and headache, Sundell, J. (1982).

The measurements of outdoor CO_2 concentration in the physical model (Katamya, Cairo) was 420 PPM, so the use of equation (2) resulting in ventilation rate per person of:
V_O =0.31/(1000-420)
=8.9 l/s (19 cfm) per person.
So if we assume 25 students and a teacher in the investigated classroom, the required supply fan will be of total capacity 19 x 26= 494 cfm (500 cfm)
The volume of the classroom is (5.7*6.9*2.7=106.2 m3 or 3749 ft3), resulting in 8 number of air change per hour.

In order to make positive pressure in the classroom, the capacity of the exhaust fan will be 10% less than the capacity of the supply fan (i.e. 450 cfm).

6. Results and Discussion

Using the CFD code, the velocity field and the contaminant concentration have been predicted. The actual velocity profiles at the three chosen levels within the students breathing zone are measured and fed to the model as inlet conditions.

The predicted results proved that the CO_2 concentration in the original case is higher than the recommended value. The CO_2 concentration decreased near the windows due do the contaminant spreading out through the windows opining. Table (1) shows that there is a good agreement between the average predicted CO_2 concentration and the average measured CO_2 concentration at the three measurement levels within the students breathing zone.

Table (1) measured and predicted concentrations at three levels for the original case

Level Number	Average Measured CO_2 Concentration (ppm)	Average Predicted CO_2 Concentration (ppm)
1	1832	1845
2	1860	1850
3	1810	1833

To improve the IAQ in the original case, four general exhaust ventilation system configurations are examined.

It is important to make the two windows and the door (which is always closed during the lessons time) closed after adding the ventilation system, because the supply fan is equipped with a filter helps in supplying the place with clean filtered air. During winter time, almost all the classes tend to shut their windows to maintain worm atmosphere in the classes.

Figure (3) shows the first configuration predicted mass fraction contours of CO_2 at the three levels. The average CO_2 concentration for the first configuration within the breathing zone is less than the predicted for the original case.

The white rectangular in figure (3) (a) is the simulation of the student's bodies, and the red spots in the figure (3) (b) are the simulation of the student's heads. The contaminated air is driven by the air streamlines towards the exhaust fan causing the recirculation of the air as seen in figures. The CO_2 gas is denser than the air, the CO_2 concentration at level 1 m should be higher than the CO_2 concentration at level 2 m, but the forced ventilation prevents the stratification to occur.

Figure (4) shows the CO_2 concentration at a longitudinal middle section in the classroom. From this figure it is clear that inspite that the average CO_2 concentration is reduced by using this configuration, but there is a region with high concentration and this means that this configuration does not satisfy a uniform CO_2 concentration distribution. Also, making the fresh air supply through the two louvers which installed at the two windows causing no control on the supply air flow rate volume as it depends on the negative pressure by the exhaust fan.

Configuration (2) provides higher average CO_2 concentration than configuration (1) as shown in the contours of the CO_2 mass fraction at the three breathing zone levels presented in figure (5), but with a more uniform CO_2 concentration distribution within the breathing zone as shown in the longitudinal section figure (6).

The predicted CO_2 mass fraction contours of configuration (3) shows a reduction in the CO_2 concentration than the original case study for the three levels as seen in figure (7). The using of four supply ceiling diffusers and one exhaust grille in the middle improved the air mixing and maintaining almost homogeneous contamination distribution as shown in the longitudinal section figure (8).

The predicted contours of the CO2 mass fraction of configuration (4), figure (9), at the three breathing zone levels show better CO_2 concentration distribution. The longitudinal section figure (10) show the homogeneity of the distribution has been improved due to use of two exhaust ceiling grille located at the case study sides, and that makes the air to be exhausted far from the supply air in order to give the supply air chance to dilute the air.

Table (2) presents the comparison between the predicted concentrations for all general exhaust ventilation system configurations.

Table (2) predicted concentrations for general exhaust ventilation system Configurations

Level Number	Configuration (1) Average Predicted CO_2 Concentration (ppm)	Configuration (2) Average Predicted CO_2 Concentration (ppm)	Configuration (3) Average Predicted CO_2 Concentration (ppm)	Configuration (4) Average Predicted CO_2 Concentration (ppm)
1	700	735	722	655
2	700	792	745	670
3	600	740	675	660

Out of this study, using distributed supply ceiling diffusers in distributing the supply air and two exhaust ceiling grilles is better in maintaining homogenous contaminant concentration and therefore improves the IAQ within the occupied zone, as better diffusion is achieved.

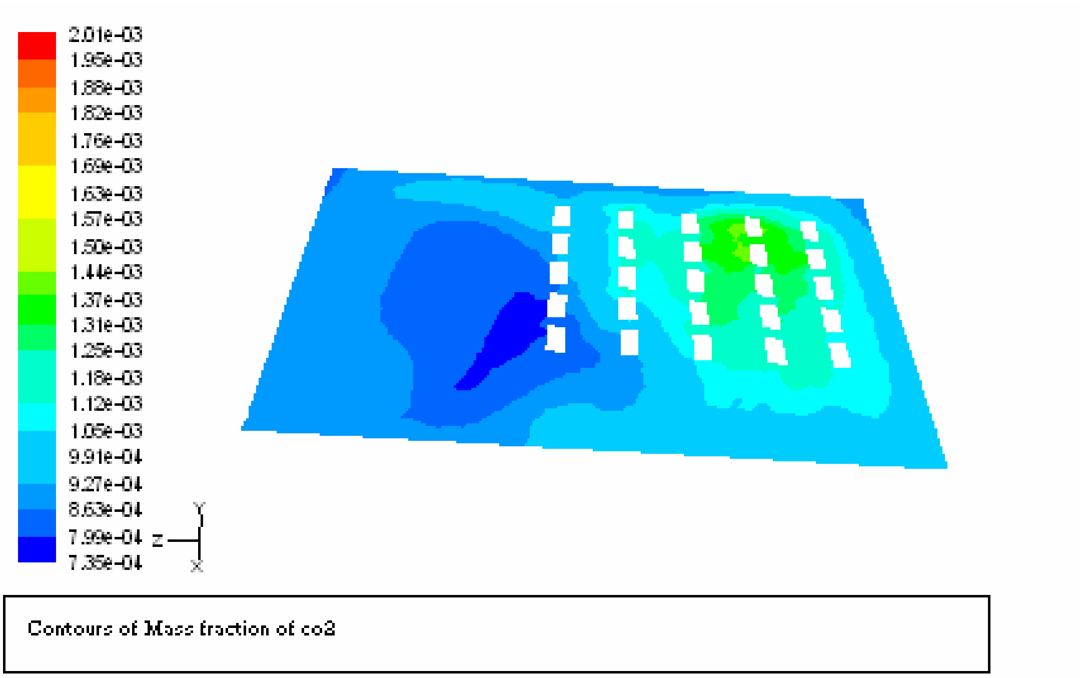


Figure (3) (a) configuration (1) predicted contours of CO_2 mass fraction (dimensionless) of the first level at height of 1 m from the ground within the students breathing zone levels

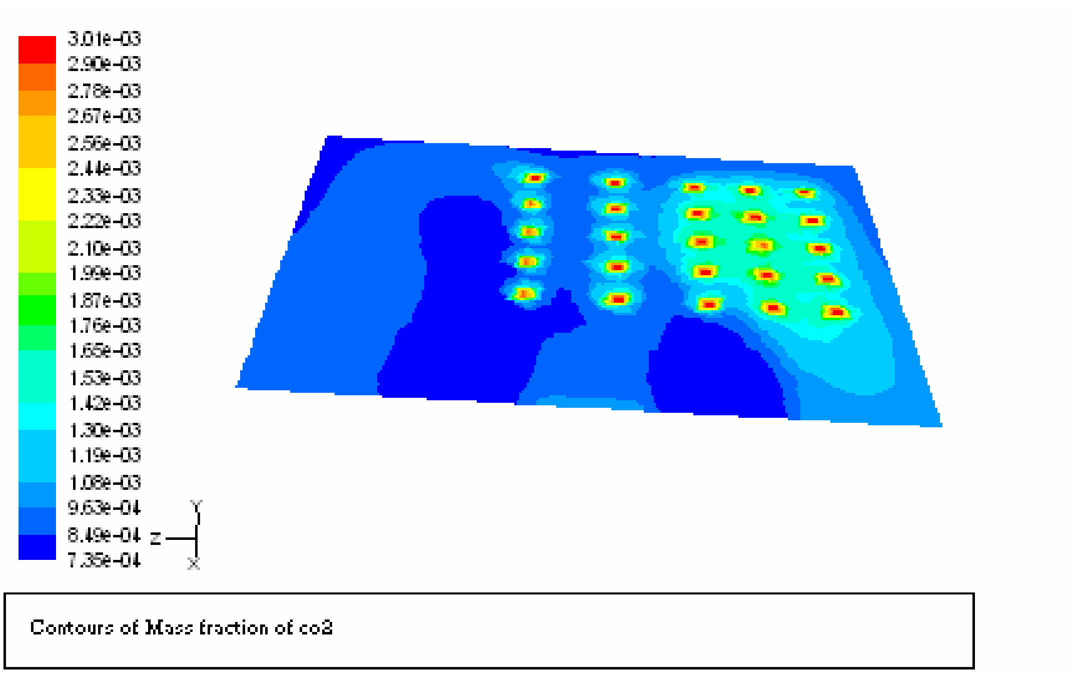


Figure (3) (b) configuration (1) predicted contours of CO_2 mass fraction (dimensionless) of the second level at height of 1.5 m from the ground within the students breathing zone levels

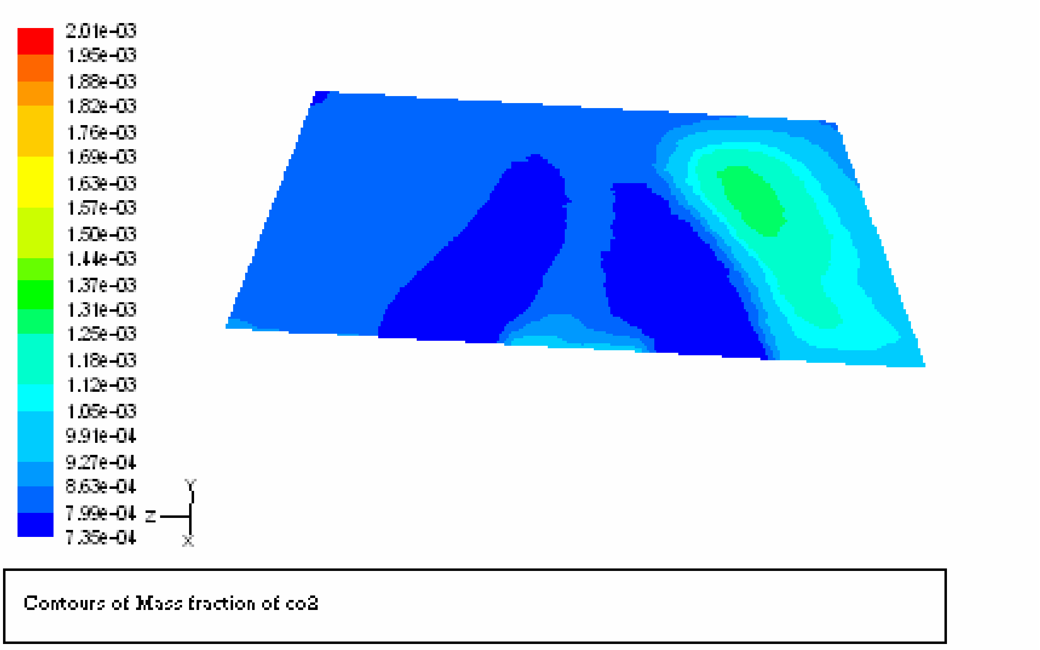


Figure (3) (c) configuration (1) predicted contours of CO_2 mass fraction (dimensionless) of the third level at height of 2 m from the ground within the students breathing zone levels

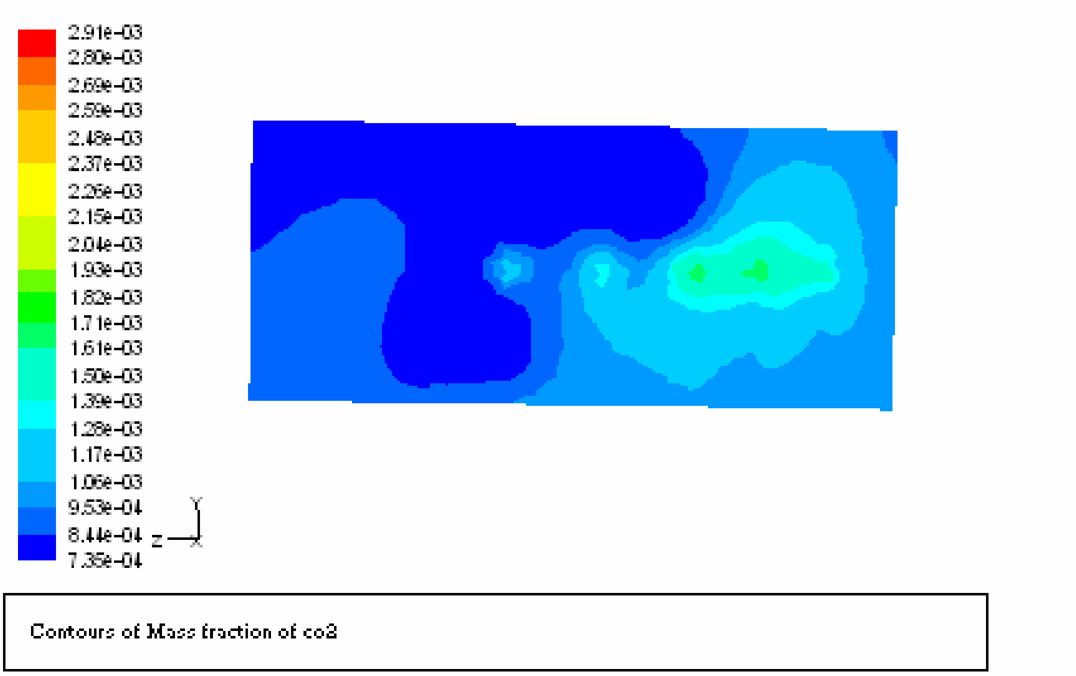


Figure (4) configuration (1), longitudinal section of predicted CO_2 mass fraction

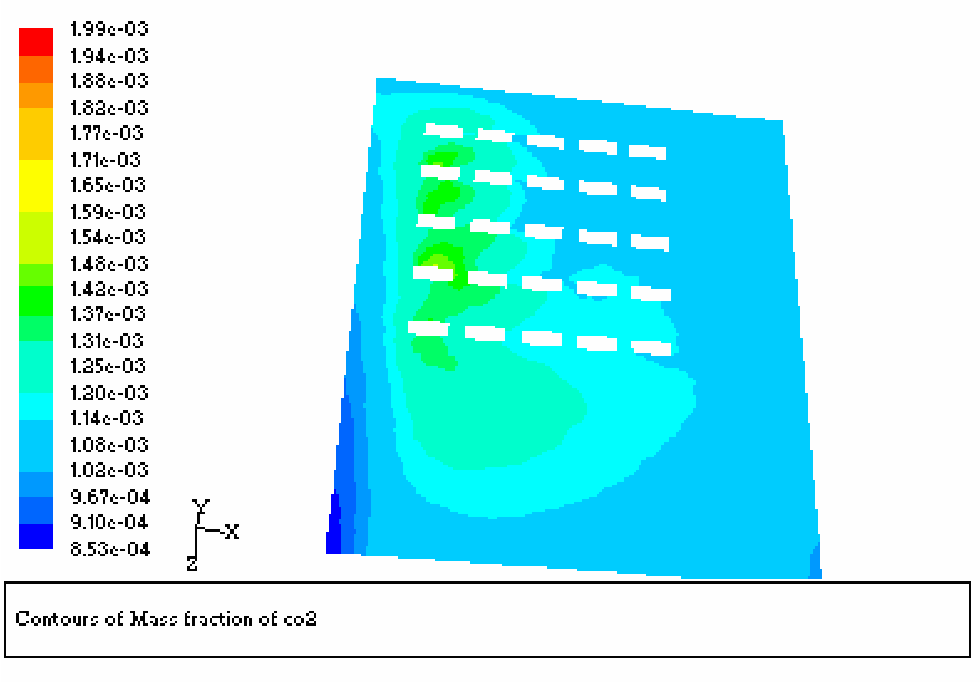


Figure (5) (a) configuration (2) predicted contours of CO_2 mass fraction (dimensionless) of the first level at height of 1 m from the ground within the students breathing zone levels

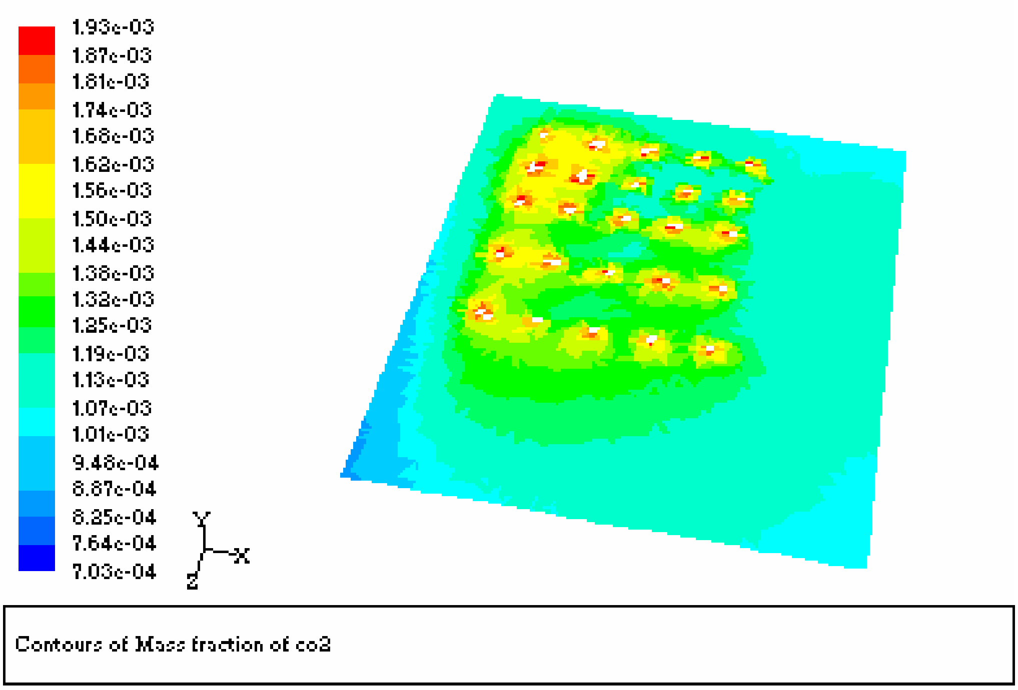


Figure (5) (b) configuration (2) predicted contours of CO_2 mass fraction (dimensionless) of the second level at height of 1.5 m from the ground within the students breathing zone levels

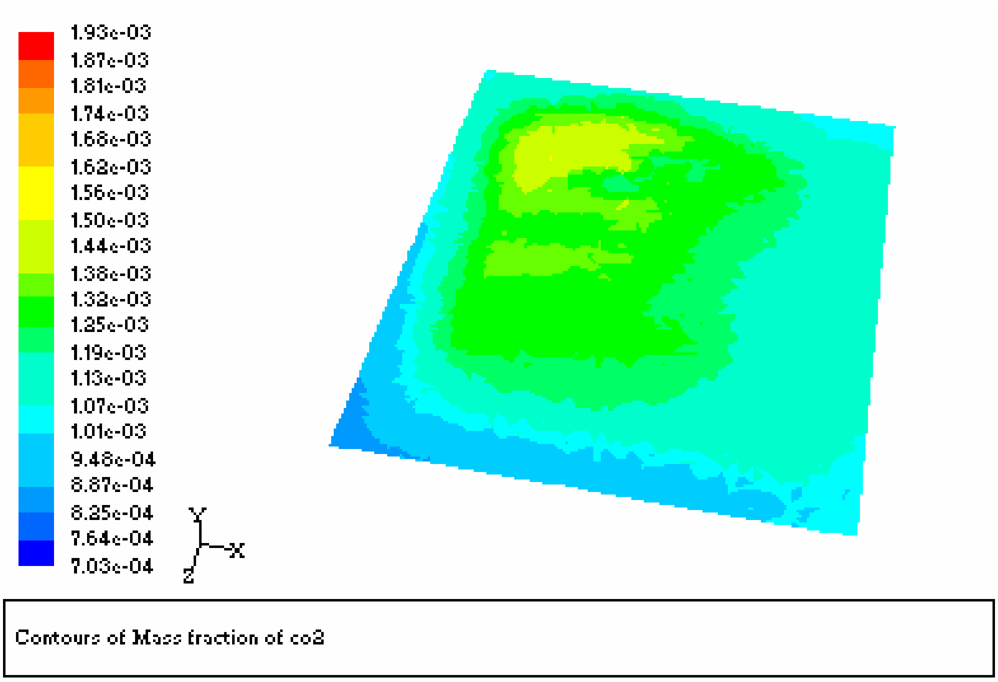


Figure (5) (c) configuration (2) predicted contours of CO_2 mass fraction (dimensionless) of the third level at height of 2 m from the ground within the students breathing zone levels

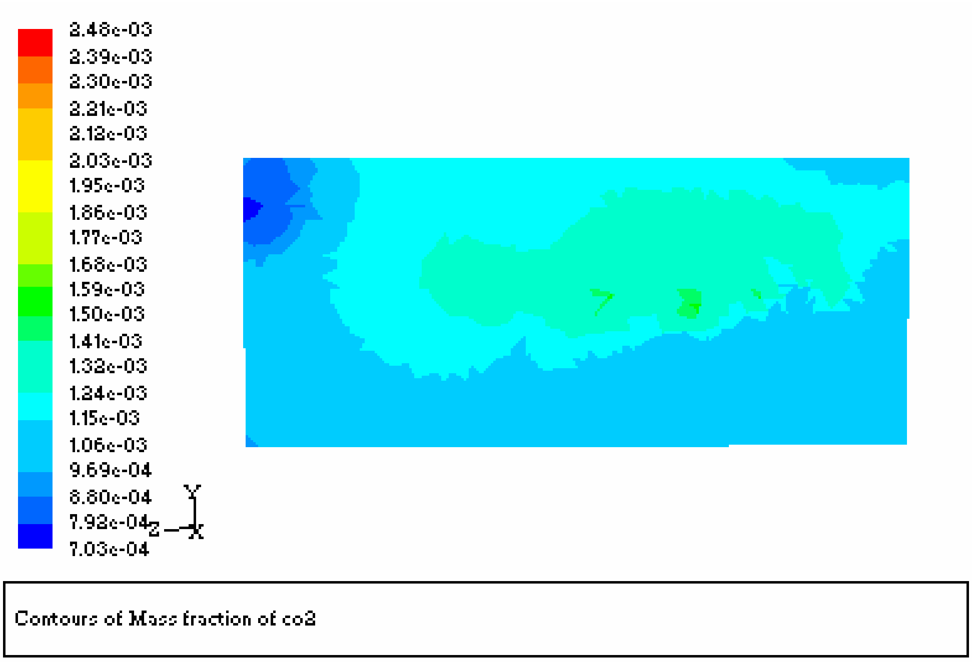


Figure (6) configuration (2), longitudinal section of predicted CO_2 mass fraction

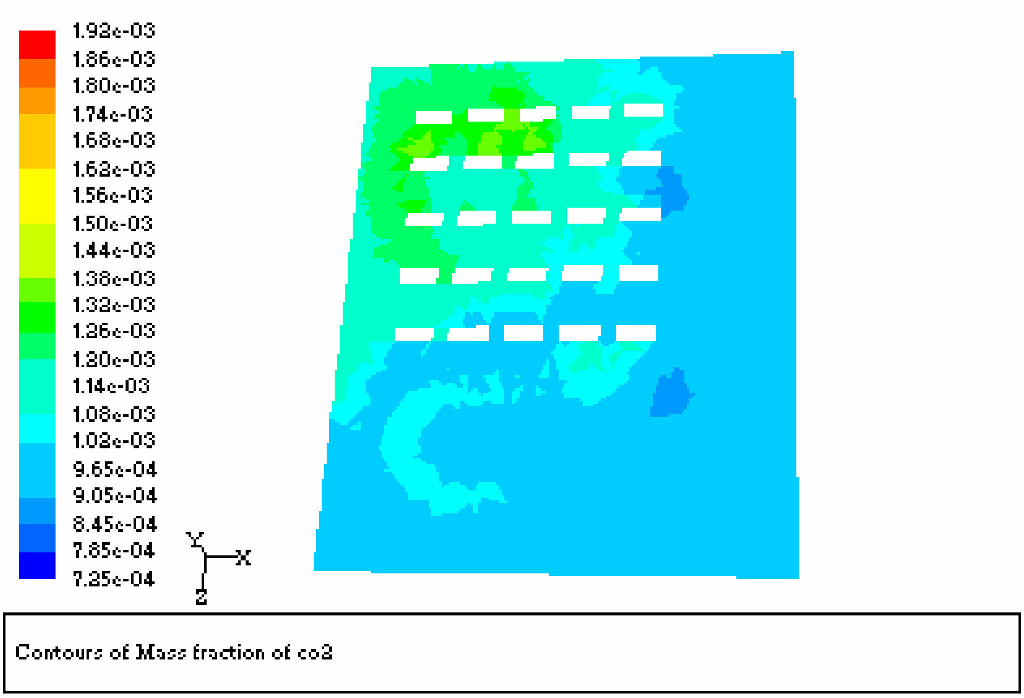


Figure (7) (a) configuration (3) predicted contours of CO_2 mass fraction (dimensionless) of the first level at height of 1 m from the ground within the students breathing zone levels

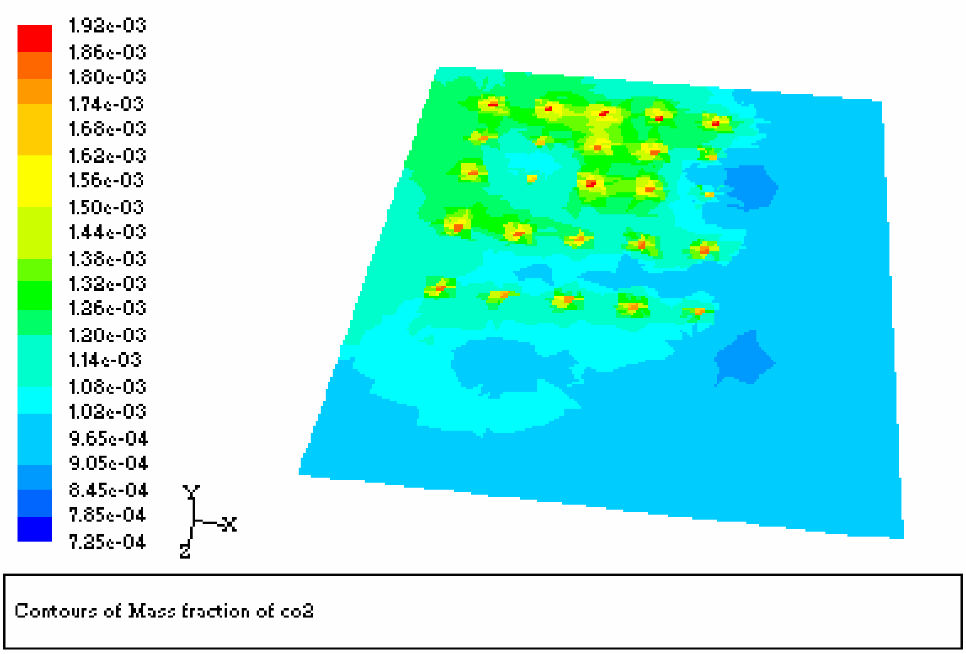


Figure (7) (b) configuration (3) predicted contours of CO_2 mass fraction (dimensionless) of the second level at height of 1.5 m from the ground within the students breathing zone levels

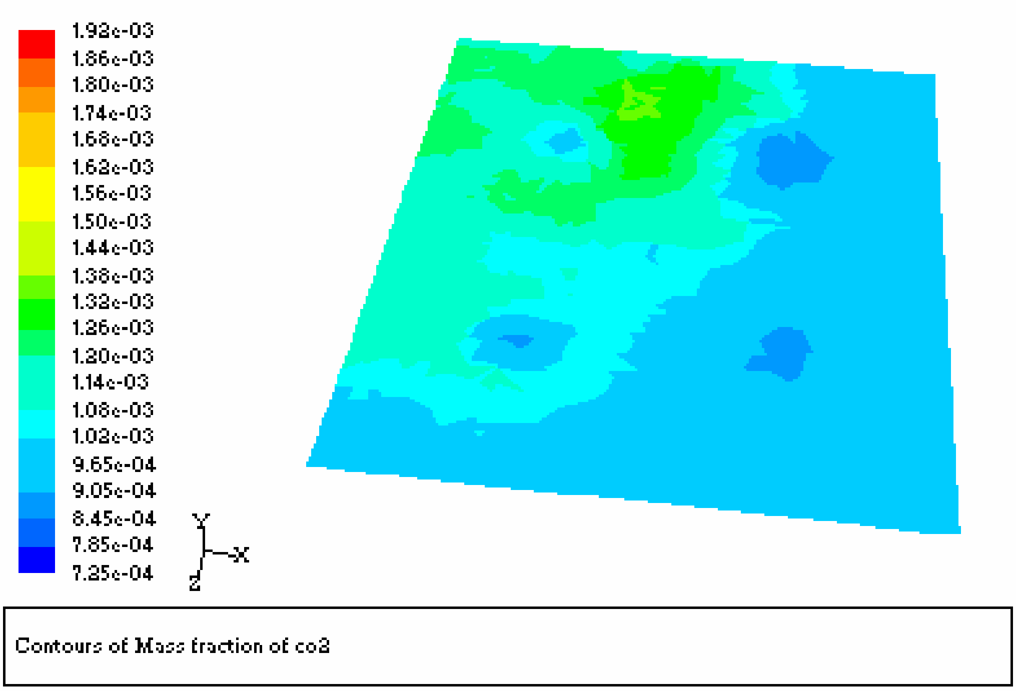


Figure (7) (c) configuration (3) predicted contours of CO_2 mass fraction (dimensionless) of the third level at height of 2 m from the ground within the students breathing zone levels

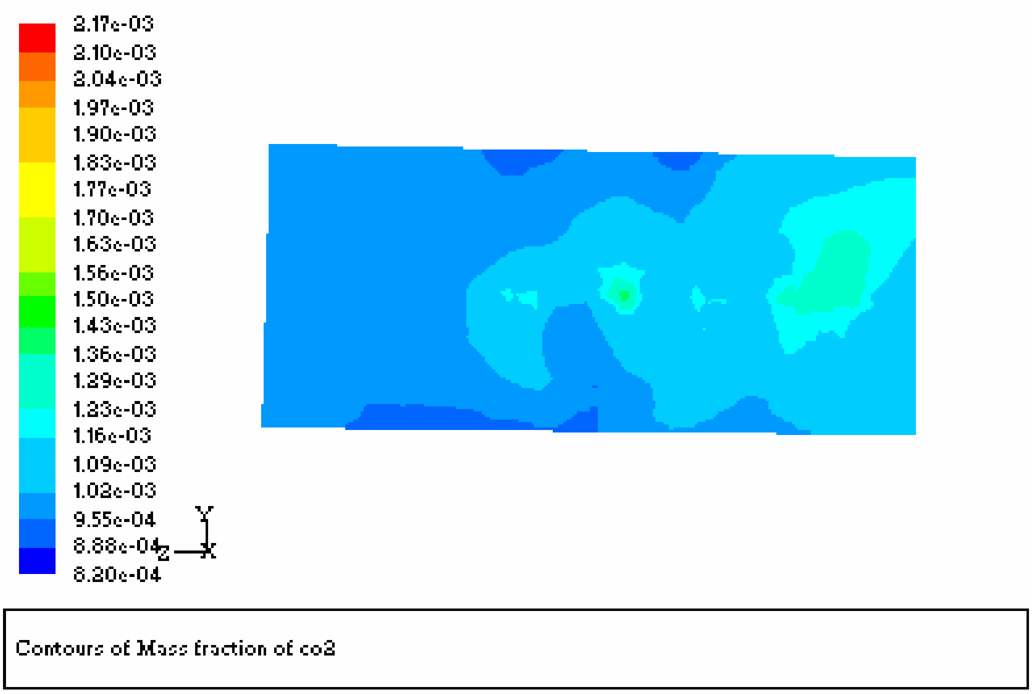


Figure (8) configuration (3) longitudinal section of predicted CO_2 mass fraction

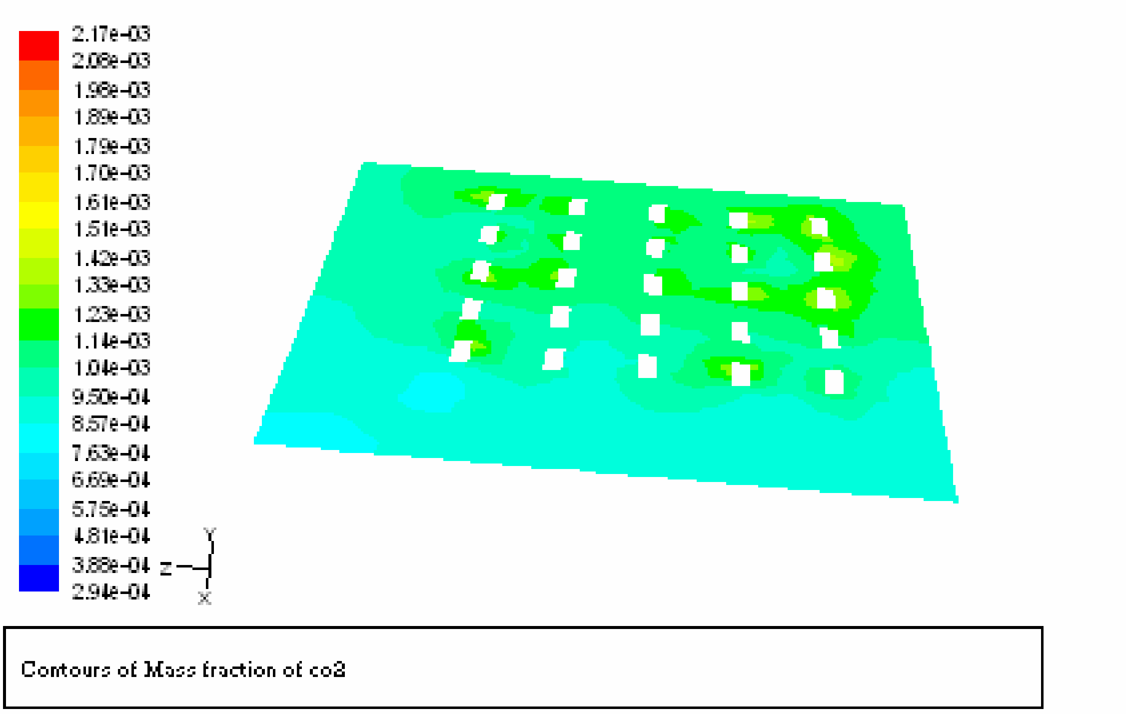


Figure (9) (a) configuration (4) predicted contours of CO_2 mass fraction (dimensionless) of the first level at height of 1 m from the ground within the students breathing zone levels

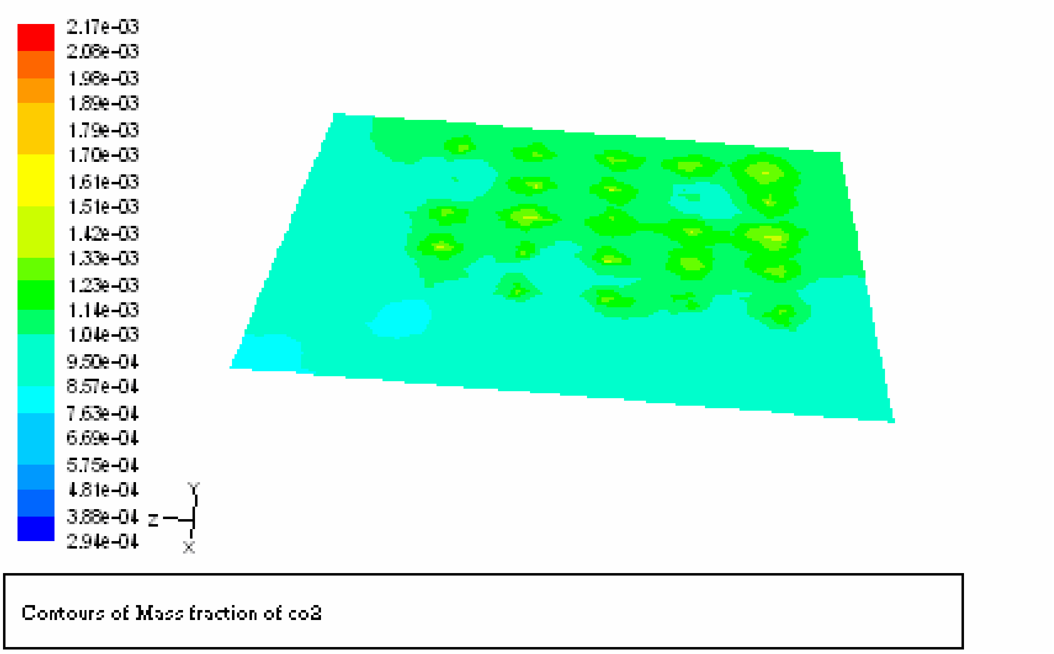


Figure (9) (b) configuration (4) predicted contours of CO_2 mass fraction (dimensionless) of the second level at height of 1.5 m from the ground within the students breathing zone levels

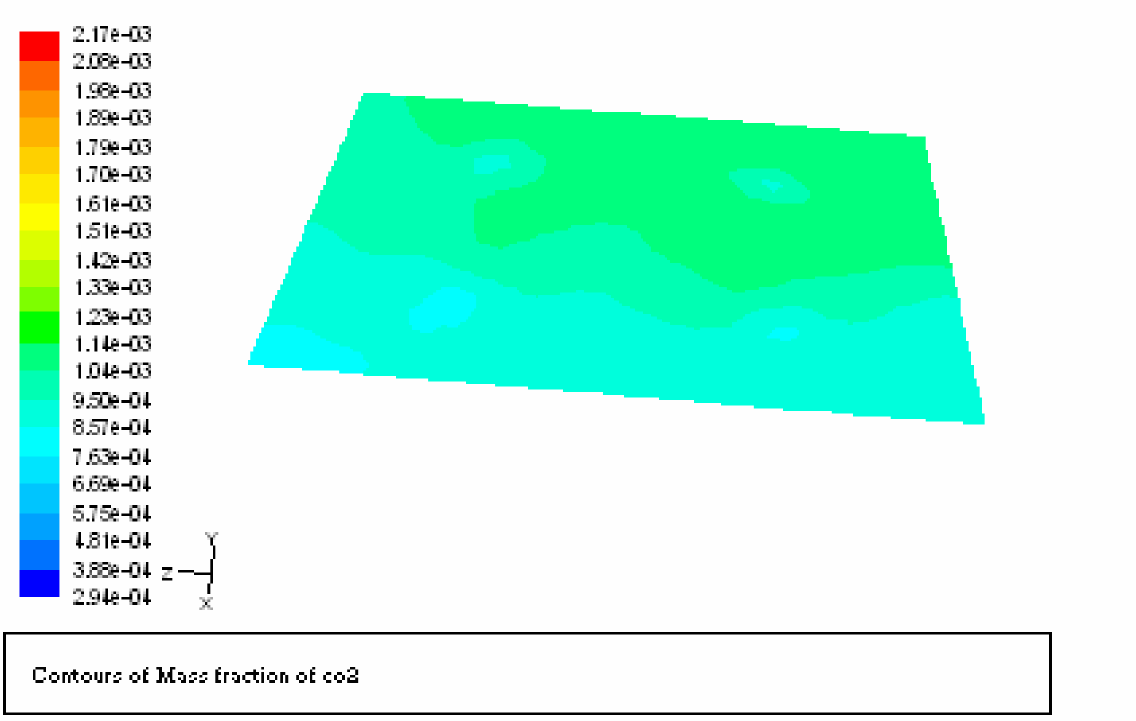


Figure (9) (c) configuration (4) predicted contours of CO_2 mass fraction (dimensionless) of the third level at height of 2 m from the ground within the students breathing zone levels

Figure (10) configuration (4) longitudinal section of predicted CO_2 mass fraction

7. Conclusion

The indoor air quality for a classroom enclosure has been investigated numerically. The numerical simulation was performed using CFD program. The simulation model has been used to predict the indoor air quality parameters distribution inside the 3-D enclosure after applying the ventilation system configuration.

The original case simulated model has been modified by applying general exhaust ventilation system configurations. The modified models have been numerically investigated to predict the indoor air quality parameters inside the enclosure.

Out of this study, it has been conducted that:

- The used CFD code is efficient in simulating and predicting the air flow pattern in a closed environment, and it can be used for Indoor Air Quality and ventilation problems.
- The contaminant concentration and the air flow pattern of the case study for the mechanical ventilation configurations were successfully simulated.
- A better Indoor Air Quality was achieved after applying mechanical ventilation system in the case study classroom.
- The optimum CO_2 concentration to obtain a better IAQ was achieved by the fourth general exhaust ventilation system configuration.
- It has been noted that during the normal school day the classroom door is usually closed adding to this, in a normal winter days the windows are also closed. These conditions leave no room for natural ventilation. Consequently the classroom air is highly contaminated with CO_2 above the ASHRAE STANDARDS limits.
  Based in the above, natural ventilation can not be considered as an effective solution for Indoor Air Quality problems.
- Mechanical ventilation is highly recommended in school classrooms to help achieving Indoor Air Quality standards.
- During the course of the study, the outdoor CO_2 concentration was more than 300 ppm, which means that the 15 cfm per person as a ventilation rate recommended by ASHRAE STANDARS can not be applied for every country. Table (3) presents some measurement of the outdoor CO_2 concentration (ppm) at Cairo and some recorded data as recorded by the Egyptian Meteorological Authority (EMA) to indicate the variation on the outdoor CO_2 concentration among countries. The required ventilation rate per person according to the outdoor CO_2 concentration is shown in figure (11).

Table (3), the required ventilation air flow rate per person for sedentary activity (school related)

Country	Outdoor CO_2 concentration (ppm)	Required ventilation air flow rate per person (cfm)
Cairo- Kobry El Koba	740	39
Cairo- Katamya	420	19
Hurghada	436	19
Qina	514	22.5
Sedy barany	454	20
Al farafra	432	19

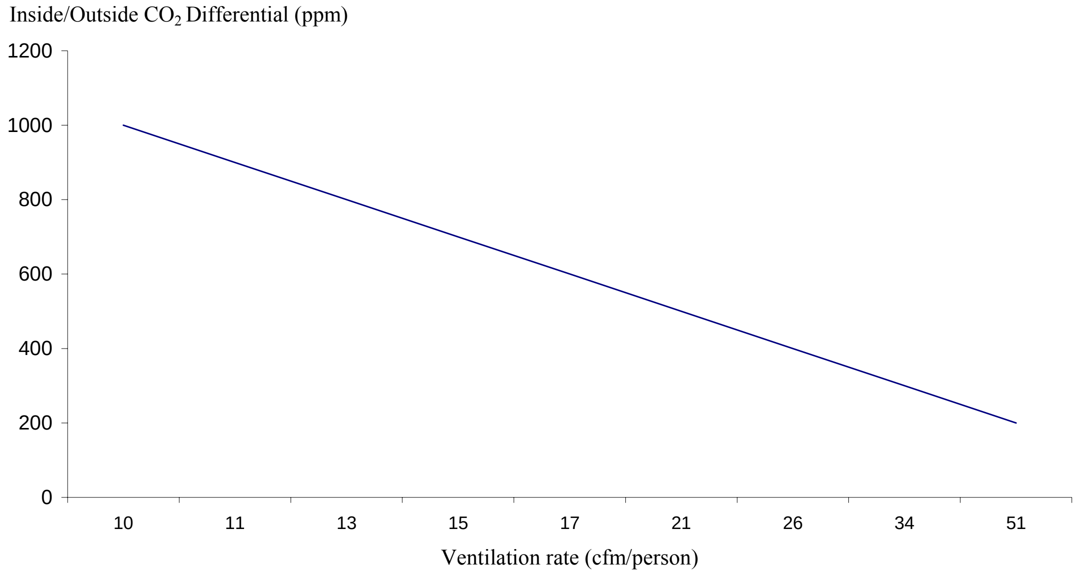


Figure (11) Ventilation rate (cfm/person) for sedentary activity (school related)

- The investigation showed the effect of the number of students in the class. The capacity of the case study classroom under investigation was not more than 25 students that mean, the IAQ problems are expected to increase in the school with higher classroom capacity.
- During the field measurement of the CO_2 concentration, it is found that there is a continuous increase in CO_2 levels with time, and this increase is depends on the classroom area and the number of students inside the classroom.

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