PREDICTION OF INDOOR ENVIRONMENTAL QUALITY OF AN OFFICE BUILDING USING COMPUTATIONAL FLUID DYNAMICS

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ABSTRACT

Buildings account for nearly 40% of the global energy consumption and 36% of carbon dioxide emissions annually. Hence presently, high emphasize is given for optimizing the performance of buildings through design of energy efficient buildings and optimum utilization of their resources. One of the fundamental criteria for assessing the performance of buildings is indoor environmental quality for human comfort and health. Indoor environmental quality is mainly governed by the ventilation performance in terms of indoor pollutant levels and thermal comfort of occupants. It is observed that people spend almost 90% of their time inside buildings, resulting indoor pollutant levels to reach 2 to 5 times higher than outdoor levels and if not addressed accordingly may lead to serious health issues. On the other hand, undesirable thermal comfort levels can affect productivity of occupants in a drastic manner, especially in an office setup. On this basis, present work analyses indoor environmental quality of an office building located in the suburbs of Colombo, Sri Lanka as per different ventilation methods using Computational Fluid Dynamics (CFD). Three dimensional computational model of the office building having 1,692,867 mixed mesh volumes, is created using *GAMBIT v. 2.2*. *EnergyPlus v. 8.0* generates building envelope temperatures to be applied as boundary conditions for the CFD simulations. *ANSYS Fluent v. 6.3* is used as the CFD tool. The k-ε RNG model predicts turbulence with enhanced wall treatment approach. Species transport model predicts dispersion of indoor emissions. The paper compares the predictions of indoor air temperature, air velocity, relative humidity, carbon dioxide concentration and Predicted Mean Vote (PMV) as per different building ventilation methods.

KEYWORDS

Performance of buildings, Indoor environmental quality, Ventilation, Computational Fluid Dynamics

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INTRODUCTION

Buildings account for nearly 40% of the global energy consumption and 36% of carbon dioxide emissions annually (Mumovic and Santamouris 2009). The built environment is booming all over Asia with China constructing almost half of the world's new buildings. The buildings in India have doubled from 2000 to 2005 (Hong et al. 2007). It is observed that buildings in Asia are consuming more energy and producing more greenhouse gas emissions and it is predicted that this will rise at a rapid rate during the next decade (Hong et al. 2007). According to IEA (2013), energy consumption for building cooling is expected to increase sharply by 2050 by almost 150% globally, and by 300% to 600% in developing countries. On this context, presently high emphasize is given for optimizing the performance of buildings through design of energy efficient buildings and optimum utilization of their resources. Performance of buildings can be analyzed based on the following fundamental criteria:

- Energy performance
- Indoor environmental quality for human comfort and health
- Environmental degradation
- Economic aspects

Following factors determine the indoor environmental quality that directly influences the physical and mental state (comfort and health) of occupants (Bluyssen 2009):

- Thermal comfort: Determined by moisture level, air velocity, air temperature etc.
- Indoor air quality: A complex phenomenon comprised of indoor pollutant levels, odour, fresh air supply etc.
- Acoustical quality: Influenced by outside and indoor noise levels, vibrations etc.
- Visual or lighting quality: Determined by view, illuminance, luminance ratios, reflection etc.

According to USDHHS (2006), during the past several years it is observed that air within buildings can be more polluted than outdoor air even in the largest and most industrialized cities. It further states that according to recent research, people spend almost 90% of their time indoors and as a result indoor pollutant levels could reach 2 to 5 times higher than outdoor levels. Hence, if not addressed accordingly, this scenario may lead to serious health issues for many occupants. According to USEPA (1995), occupants exposed to indoor air pollutants for the longest periods are those who are most vulnerable to such effects. Such occupants include young children, elderly people and patients suffering from respiratory or cardiovascular diseases. On the other hand, undesirable thermal comfort levels can affect productivity of occupants in a drastic manner, especially in an office setup. Also, high temperature and humidity levels increase the concentration of certain pollutants in the indoor environment as revealed by USDHHS (2006).

Indoor environmental quality can be optimized by enhancing the ventilation performance of buildings. Computational Fluid Dynamics (CFD) is a powerful tool that is capable of assessing the ventilation performance of a building that enables the designers to optimize the indoor environmental quality. On this basis, the paper analyses indoor environmental quality of an office building located in the suburbs of Colombo, Sri Lanka as per different mechanical ventilation methods using CFD. However, the study focuses only on the predictions related to thermal comfort and indoor air quality of the building under consideration.

GOVERNING PRINCIPLES

Energy Balance of Building Envelope Surfaces

Energy balance for a particular surface of the building envelope is shown in Figure 1 (Zhai and Chen 2001). Energy balance equation takes the form as given in equation 1.

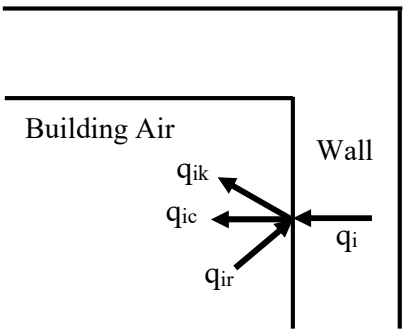

***Figure 1**. Energy balance of a building envelope surface (Zhai and Chen 2001)*

$$q_i + q_{ir} = \sum_{k=1}^{N} q_{ik} + q_{ic} \tag{1}$$

Where q_i and q_{ic} are conductive and convective heat flux from surface i respectively. q_{ir} is the radiative heat flux from internal heat sources and solar radiation. q_{ik} is the radiative heat flux from surface i to surface k. N is the number of such surfaces in the building envelope. Surface temperatures of the building envelope are obtained by solving aforementioned energy balance equations by the energy simulation tools.

Computational Fluid Dynamics

In CFD, numerical techniques are applied for solving Navier-Stokes equations for fluid flow and heat transfer. Navier-Stokes equations are derived through the application of conservation laws of mass (continuity), momentum and energy to a fluid control volume. In addition, relevant transport equations to predict turbulence, species transport etc. may be incorporated depending on the problem being handled. The governing equations take the general form as in equation 2 (Zhai and Chen 2001).

$$\frac{\partial \phi}{\partial t} + (V.\nabla)\phi - \Gamma_\phi \nabla^2 \phi = S_\phi \tag{2}$$

Where t, ϕ, V, Γ_ϕ and S_ϕ are time, general transport variable, velocity vector, diffusion coefficient and source term respectively. The numerical solution for the flow field is established after solving all transport equations through an iterative process.

METHODOLOGY AND APPROACH

Energy Simulation Model

The single-storey office building under consideration has overall dimensions of 8.0 m x 6.0 m x 3.5 m. Energy simulation model of the building, having a single thermal zone, was created using *Google SketchUp* v. 8.0 with *OpenStudio* plug-in v. 1.0.7 and is shown in Figure 2.

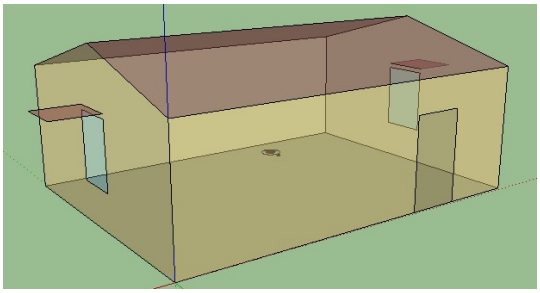

***Figure 2**. Energy simulation model of the building*

Inputs to the model were given through both *Google SketchUp* and *IDF Editor* of *EnergyPlus* (Crawley et al. 2001). Weather information was incorporated to the model through the *.epw* file available for Ratmalana area. Tables 1 and 2 show the details of thermal and electrical loads and construction details of the building respectively.

***Table 1.** Thermal and electrical loads of the building*

Load/System	*Rating and Description*
Occupancy	10 Nos. of people involved in general office work with a specified occupancy schedule
HVAC system	Standard chilled water system
Artificial lighting	150 W
Electrical equipment rating	400 W

***Table 2.** Construction details of the building*

Building Element	*Construction Details*
Walls	9 inch thick standard brickwork
Floor	10 mm thick ceramic tiles on a 150 mm thick reinforced concrete slab
Roof	Pitch angle of 15^0 with 25 mm thick Calicut tiles
Door	1.1 m x 2.0 m made of plywood
Windows	0.5 m x 1.0 m double pane windows of 4 mm thick glass and 2 mm thick air space
Shading overhangs	Depth 0.5 m and tilt angle of 90^0

EnergyPlus (Crawley et al. 2001) v. 8.0 is used as the energy simulation tool during present work. It is a new generation building energy modelling tool based on *DOE – 2* and *BLAST* that was first released in 2001. *EnergyPlus* is capable of predicting the internal surface temperatures of the building envelope elements which are applied as

boundary conditions for the CFD simulations. Energy simulation was performed for the scenario that records the highest annual outdoor dry bulb temperature (Occurring on 19th April at 12.10 pm) in terms of the weather file for the Ratmalana area and the corresponding internal surface temperatures of the building envelope were predicted.

CFD Model

The CFD model of the building was created using *GAMBIT v. 2.2* and is shown in Figure 3. It consists of 1,692,867 mixed mesh volumes in the computational domain. Separate boundary meshes were created for each surface of the building envelope. *ANSYS Fluent v. 6.3* was applied as the CFD tool during the analysis.

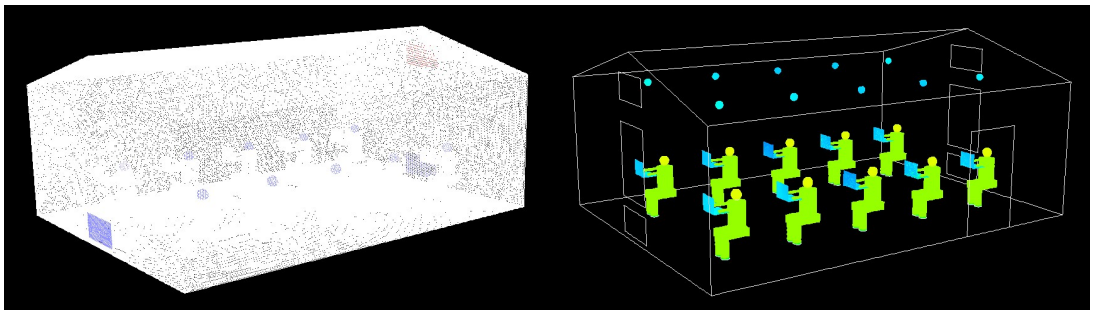

***Figure 3**. CFD model of the building*

Table 3 shows modelling parameters and boundary conditions used for the CFD simulations. A user defined function (UDF) to calculate thermal comfort of the occupied space was created using the *C* language and it was subsequently integrated to *ANSYS Fluent* using *Visual Studio 9.0*.

***Table 3.** Modelling parameters and boundary conditions*

Parameters/Boundary conditions	*Model/Value*
Supply air temperature	16 ^{0}C
Supply air relative humidity	90%
Turbulence model	k-ε RNG
Discretization scheme	QUICK
Near-wall treatment	Enhanced wall treatment
Diffusion of emissions	Species transport model
Internal surface temperatures of the building envelope (predicted by EnergyPlus)	
North wall	29 ^{0}C
South wall	29 ^{0}C
East wall	29 ^{0}C
West wall	30 ^{0}C
Floor	25 ^{0}C
North part of roof	47 ^{0}C
South part of roof	47 ^{0}C
Door	35 ^{0}C
East window	31 ^{0}C
West window	31 ^{0}C
Mass flow rate of exhaled air	2.6 x 10^{-4} kg/s per occupant
Relative humidity of exhaled air	Saturated state
Species mass fractions of emissions from occupants	
CO_2	0.050
H_2O	0.035
N_2	0.755
O_2	0.160

SIMULATION RESULTS

CFD simulations were performed as per different configurations of mechanical ventilation and Figures 4 to 10 show the respective predicted airflow fields.

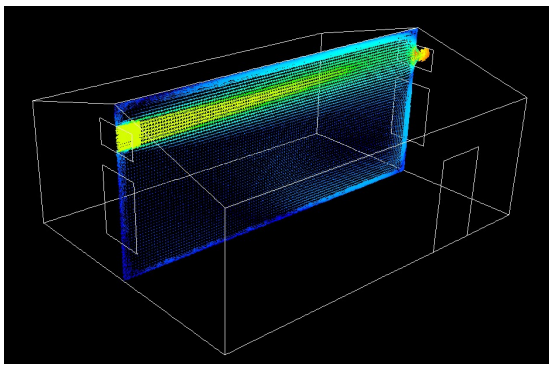

***Figure 4**. Cavity flow ventilation*

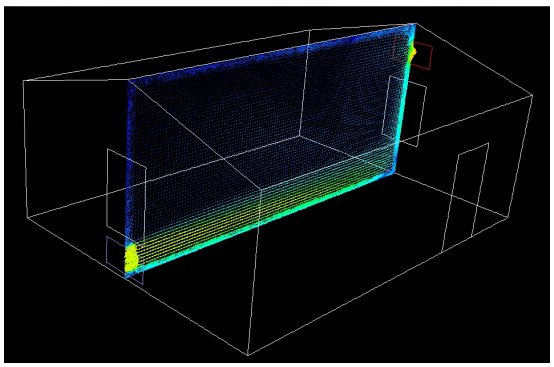

***Figure 5**. Displacement ventilation-Case1*

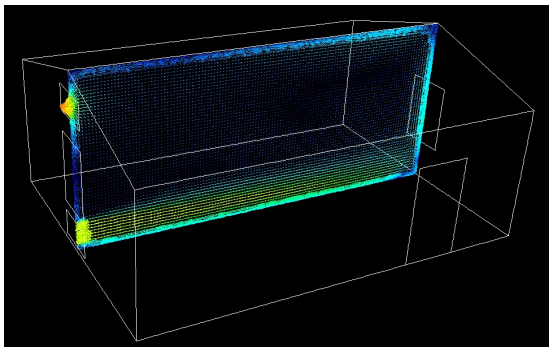

***Figure 6**. Mixing flow ventilation-Case1*

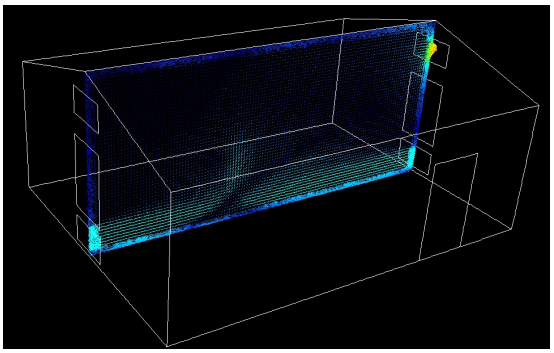

***Figure 7**. Mixing flow ventilation-Case2*

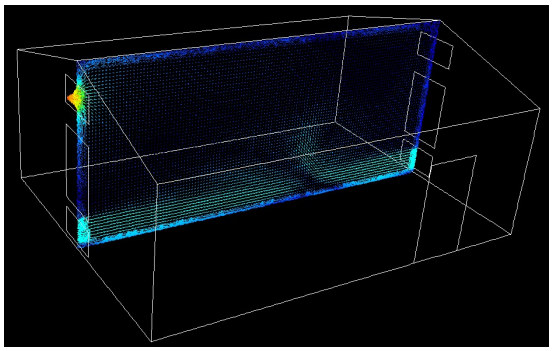

***Figure 8**. Mixing flow ventilation-Case3*

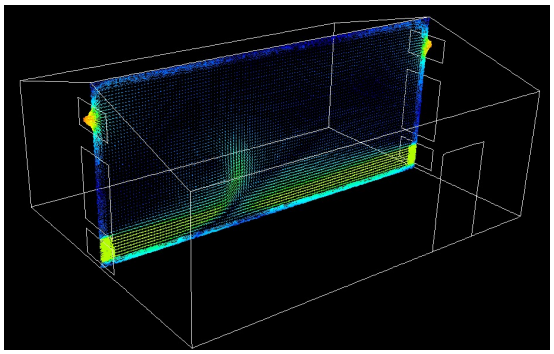

***Figure 9**. Mixing flow ventilation-Case4*

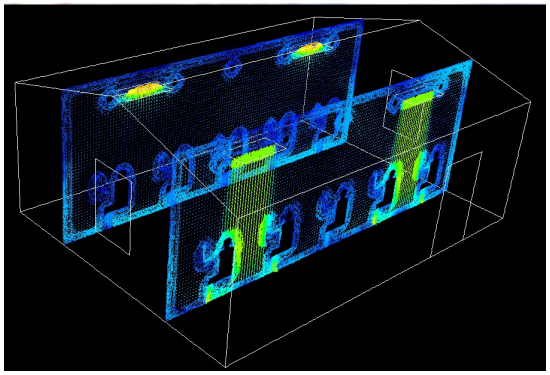

***Figure 10**. Displacement ventilation-Case2*

Comparison of the average indoor environmental quality parameters related to vertical occupant planes among different ventilation configurations is shown in Table 4.

Table 4. *Comparison of average values of indoor environmental quality parameters*

Configuration of ventilation	*Air Temperature (^0C)*	*Air Velocity (ms^{-1})*	*Relative Humidity (%)*	*CO_2 Level (ppm)*	*Thermal Comfort (PMV)*
Cavity flow	28.8	0.017	55.8	9.2	1.90
Displacement flow-Case 1	28.6	0.021	52.8	7.2	1.88
Displacement flow-Case 2	21.3	0.081	68.0	3.8	0.89
Mixing flow-Case 1	27.4	0.021	57.6	7.9	1.74
Mixing flow-Case 2	23.1	0.030	66.9	5.3	1.20
Mixing flow-Case 3	23.0	0.031	68.8	5.8	1.18
Mixing flow-Case 4	22.7	0.031	70.9	6.2	1.14

Figures 11 and 12 show the predicted thermal comfort and CO_2 emission profiles on vertical occupant planes for displacement flow ventilation – case 2.

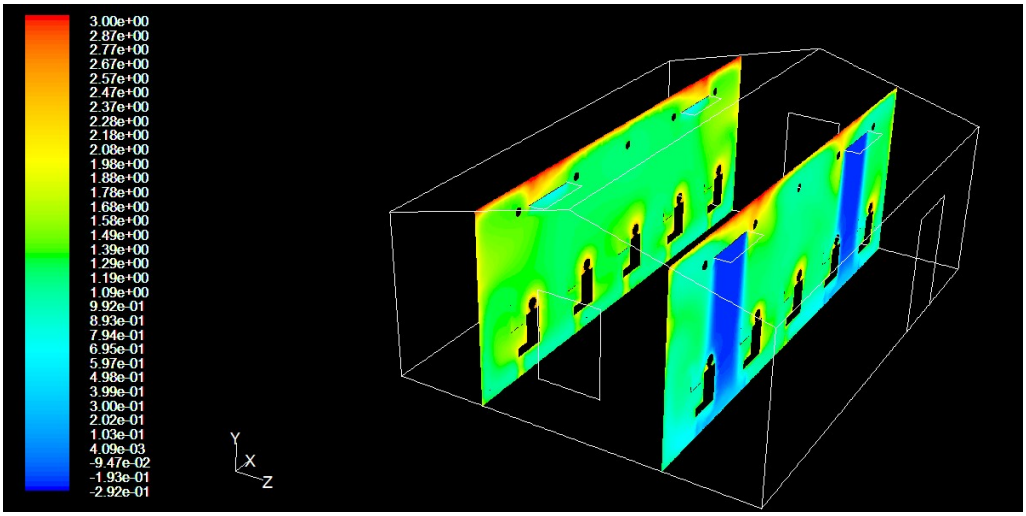

Figure 11*. PMV thermal comfort profiles in displacement ventilation-case 2*

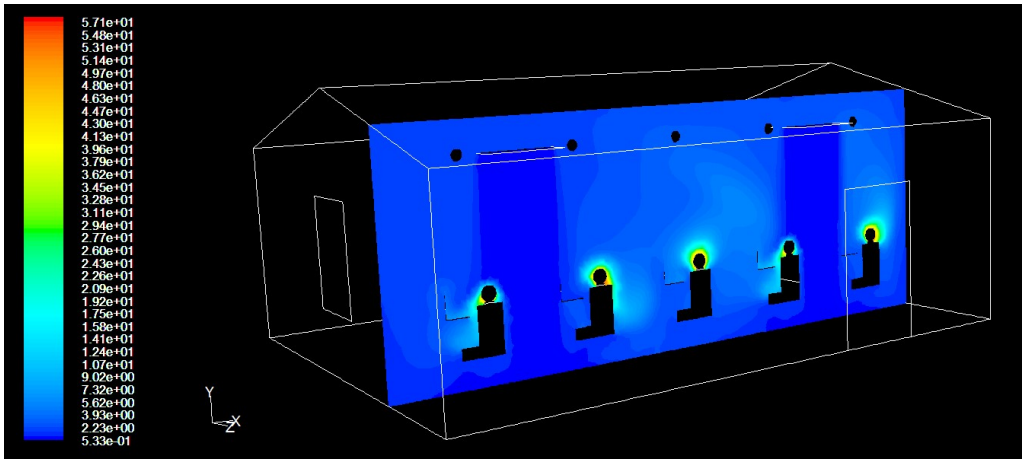

Figure 12*.* CO_2 *profiles (in ppm) in displacement ventilation-case 2*

DISCUSSION

Modelling of indoor environmental quality has been performed for the scenario with maximum annual outdoor dry bulb temperature of the building location. The results show that the best indoor environmental quality on vertical occupant planes has been predicted for the displacement flow - case 2 in terms of both thermal comfort and indoor air quality. Although for this case a higher relative humidity is predicted (68%), the best PMV is however expected due to low air temperature and relatively higher air velocity compared to other configurations. It is also expected to record the lowest CO_2 level for this case. The CFD solution was also checked against *grid independence*. However, emissions from building envelope materials were not considered during the study.

CONCLUSION AND IMPLICATIONS

The work may provide some general guidance for building designers in terms of the influence of the mechanical ventilation configuration on ventilation performance of a simple building and eventually on the indoor environmental quality for human comfort and health. The computational model can be further refined by validating the CFD predictions through experimental measurements in order to predict more realistic results. This will be the next step of the present endeavour.

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