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Efficacy of CFD in estimating thermal behavior of a naturally ventilated house

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Abstract — *In this age of ever depreciating conventional energy sources and increased problems of climatic conditions, the need for conservation of energy and confronting indoor air quality has become irreplaceable from the civil purpose. Therefore, it becomes very important to incorporate computational analysis while designing buildings and homes, which will help to maintain optimum control over internal climatic conditions along with the efficient utilization of energy. This work aims at studying one such idea, to analyze the building design before erection from the perspective of maintaining optimum thermal comfort to the human body, with the help of Computational Fluid Dynamics and therefore further providing suggestions for improvements in optimizing the energy consumption based on design changes prior to the actual implementation. Qualitative measurements for optimum building design are studied in terms of physical variables like PMV and PPD to get conclusive results on indoor air quality.*

Keywords- *Natural ventilation, Predictive Mean Vote (PMV), Thermal comfort analysis, Indoor air quality, Computational Fluid Dynamics (CFD)*

I. INTRODUCTION

The analysis of indoor air quality using the P. Fanger's suggested Predicted Mean Vote (PMV) model, which is considered as a standard for determining the thermal comfort zones by ASHRAE [2], furnishes a precise outcome with the inclusion of all the variables affecting the comfort condition of the human being. The energy consumption in HVAC systems for the residential building is nearly about 68% of the total consumption, as per the recently presented data [3]. Naturally ventilated buildings have a reduced amount of the energy consumption requirement for HVAC system. Therefore it is necessary to analyze the building geometry for the requisite of the HVAC system and improve the design for influencing the natural ventilation. CFD analysis of the building for the thermal behavior under the naturally ventilated conditions provides a better transition towards the scrutinized vision for estimation of HVAC loads and in the same way, comfort conditions as derived from the predicted mean vote.

This paper presents the investigation of the natural ventilation and the thermal comfort characteristics for the single-zoned building geometry with cross ventilation provided with the two openings – one at the windward face and another one at the leeward face of the building, with the climate conditions for the Delhi, India.

II. METHODOLOGY

2.1. General

Wind tunnel experiment for assessment of the air-flow natural ventilation was carried out by Karava et al. [2] with the Particle Image Velocimetry (PIV) measurements at Concordia University, Montreal, Canada. A generic single-zone building model was tested for iso-thermal flow conditions with only wind driven natural ventilation. The computational parameters, which are used for the simulation of cross ventilated generic building model using Ansys Fluent, are discussed as bellow. These parameters are derived based on the experimental investigation of basic cross ventilation characteristics for the single-zone building model in the wind tunnel under isothermal flow conditions [2].

2.2. Computational Domain

The computational domain is set up at the reduced level (1:200) same as the wind tunnel geometry. The dimensions of the domain are 0.9×1.54×0.48 m^3. The geometry of the building model used for the analysis is shown in the figure 1 and the dimensions of the control volume are shown in figure 2. The grid is prepared by using structured algorithm for the better control of every nodes and elements.

2.3. Validation and Grid Independence study

The results of the CFD analysis for the isothermal flow condition is compared with the experimental data available from the wind tunnel experiment [2]. The figure 3 shows the comparison of the velocity at the center-line of central plane of the domain. The grid independence study is also done by computing the same model with increment and decrement of grid counts by 30%. The comparison of the velocity obtained from simulations at the center-line of central plane of the domain is shown in the figure 4. The turbulence equations and the boundary conditions used for the simulation are described in the following sessions.

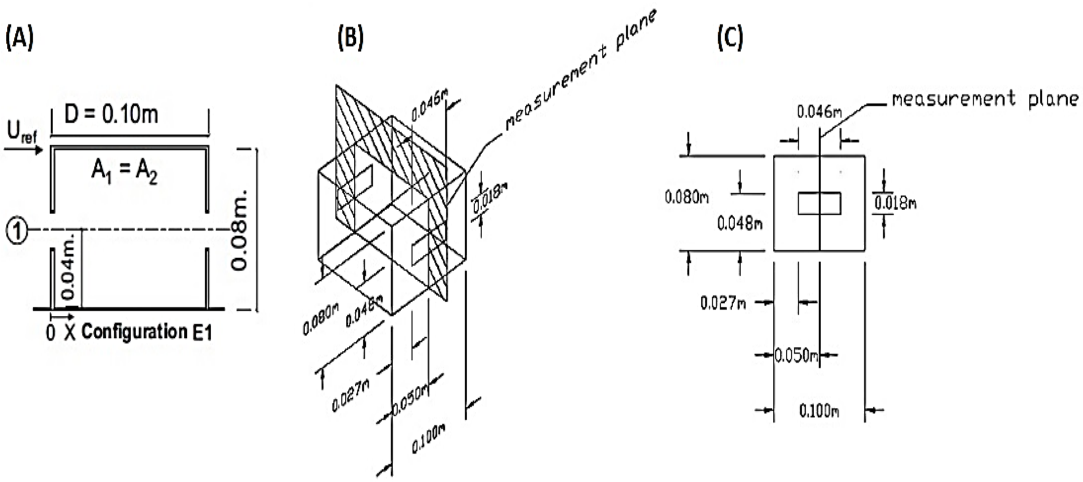


Figure 1. (A) Vertical cross-section of the reduced scaled building model as studied by Karava et al. [2] with opening size and dimensions (in meters) with center-line (1). (B) Front view of the reduced-scaled building model with opening size and dimensions (in meters). (C) Prospective indicating the measurement plane

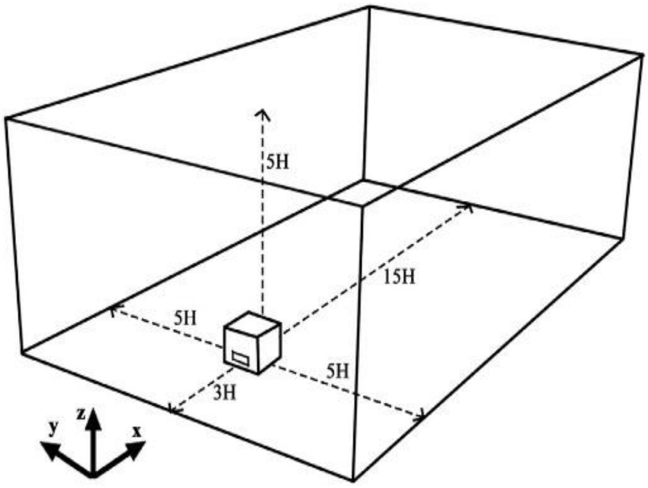


Figure 2. Perspective view of the building in its computational domain at model scale

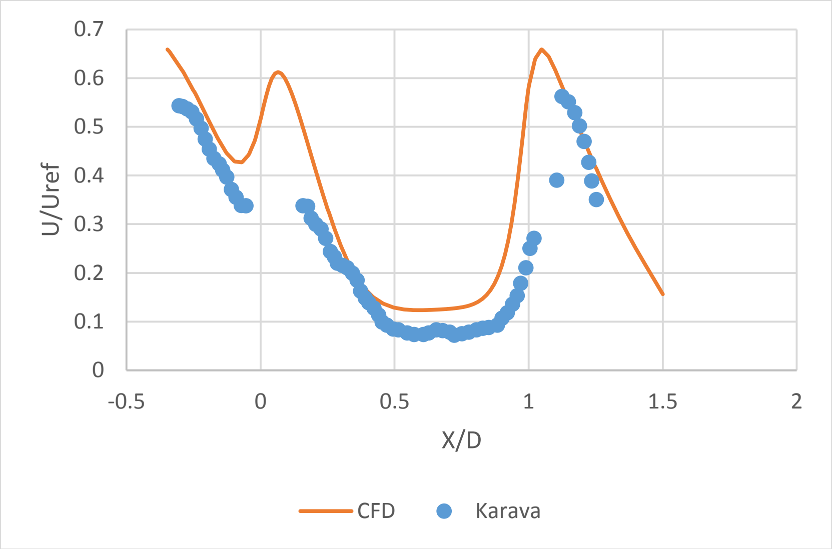


Figure 3. Profile of velocity component on the center-line directly between the inlet and outlet openings based on PIV measurement on a horizontal plane and a vertical plane and Profile of velocity component obtained from CFD simulation

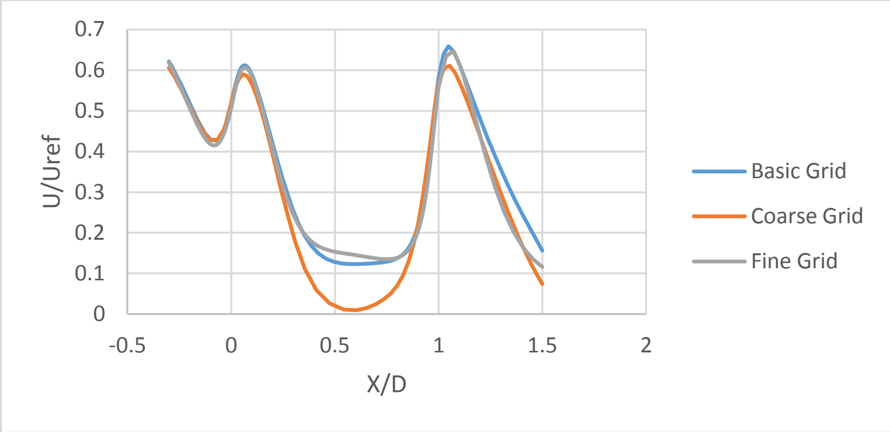


Figure 4. Grid independence analysis with ±30% grid density modification

2.4. Turbulence Models and Solar Radiation

For the investigation of the isothermal flow characteristics, the standard k-epsilon with the two transport equations can be used. The study represented by J.I. Perén [3] suggests that shear stress transport k-ω and the renormalization-group (RNG) k-epsilon models shows better agreement with the experimental data. But for the inclusion of the solar heat flux on the building, the realizable k-epsilon turbulence model shows the better results with the experimental data as the study presented by G. Evo [4]. The solar radiation is introduced as per the location of the Delhi and the various radiation values are presented in table 1. Here, the weather data is taken as the average values during the month of May (summer season), at the noon time.

Table 1. Orientation and value of solar radiation and weather conditions

Sun direction vector	X: 0.3252, Y: 0.9439, Z: 0.0566
Sun shine factor	1.0
Diffuse solar irradiation (Vertical surface)	85.463 W/m2
Diffuse solar irradiation (Horizontal surface)	117.332 W/m2
Ground reflected solar irradiation – Vertical surface	94.3845 W/m2
Ambient temperature312.2 K	312.2 K
Relative humidity	33%
Wind velocity	3 Beaufort (4.45 m/s)

2.5. Boundary Conditions

The velocity profile provided at the upwind boundary layer, is having logarithmic profile as a function of the height h.

$$U(h) = \frac{U_o}{K}\log\left(\frac{h+h_o}{h_o}\right) \quad (1.0)$$

Where, K is Von Karman constant (K = 0.42). U_o is Atmospheric Boundary Layer velocity which is derived from the reference value of the velocity (U_o= 0.35 m/s). h_o is the reduced-scale aerodynamic roughness length (h_o = 0.025 mm) [2].

The profiles of kinetic energy (k), the dissipation rate (ε) and the specific dissipation rate (ω) are given by the following equations:

$$k(h) = \frac{3}{2}(T_i \cdot U(h)) \quad (2.0)$$

$$\varepsilon(h) = \frac{(U_o)^3}{K(h+h_o)} \quad (3.0)$$

$$\omega(h) = \frac{\varepsilon(h)}{C_\mu \cdot k(h)} \quad (4.0)$$

Where, T_i is the turbulence intensity and C_μ is the empirical constant (C_μ = 0.09). According to the literature [5], the value of T_i is taken as 4% .

The air is taken as humid air (mixture of dry air and water vapour) and thermal diffusion is considered by calculating species transport equations along with the 3D steady Reynolds-averaged Navier-Stokes equations and realizable k-epsilon turbulence model.

At the outlet, a constant pressure profile is assumed with the zero gauge pressure. All the gradient present in the upwind boundary layer are also assumed to be vanished at the outlet of the domain. The other planes of the control volume are set as the symmetry boundary condition which provides zero value for the normal gradient of any quantity.

III. RESULTS AND DISCUSSION

3.1. Ventilation Analysis (Ventilation rate)

An empirical model [4] for the estimation of ventilation rate for cross ventilated system can be given by,

$$Q_{CR} = C_d \cdot A_{eff} \cdot \bar{U} \cdot \sqrt{\Delta C_P} \qquad (5.0)$$

Where, C_d is the discharge coefficient (which can be taken as 0.61 for sharp openings). ΔC_P is the difference between the values of pressure coefficient on both the openings. A_{eff} is the effective area of the openings and can be expressed as

$$\frac{1}{A_{eff}^2} = \frac{1}{A_{in}^2} + \frac{1}{A_{out}^2} \qquad (6.0)$$

Calculating the equation (5.0), the ventilation rate for this case is 41.47 lit/s, which is quite higher than the required ventilation rate for a day room as per ASHRAE Standards (15 lit/s) [6].

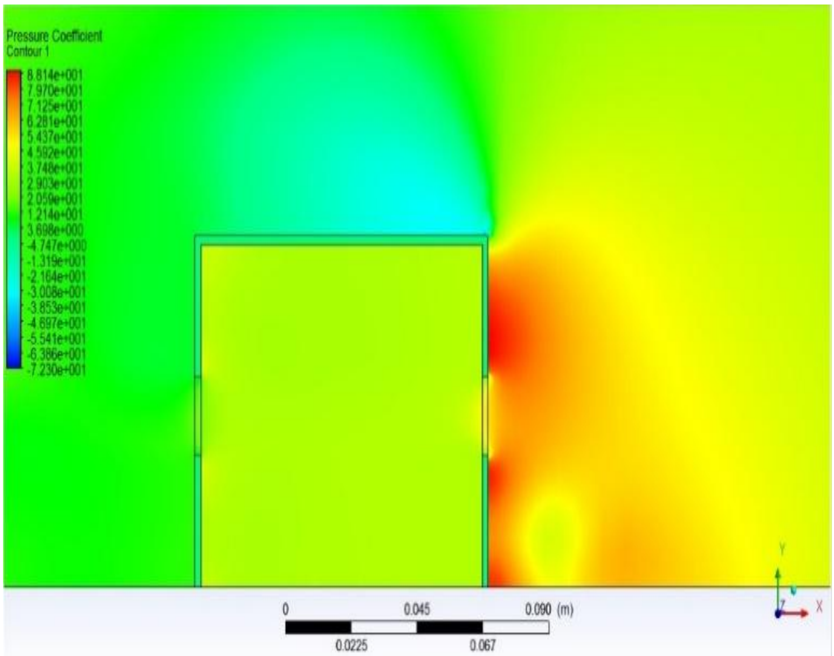


Figure 5. Contours of pressure coefficient at the center-plane

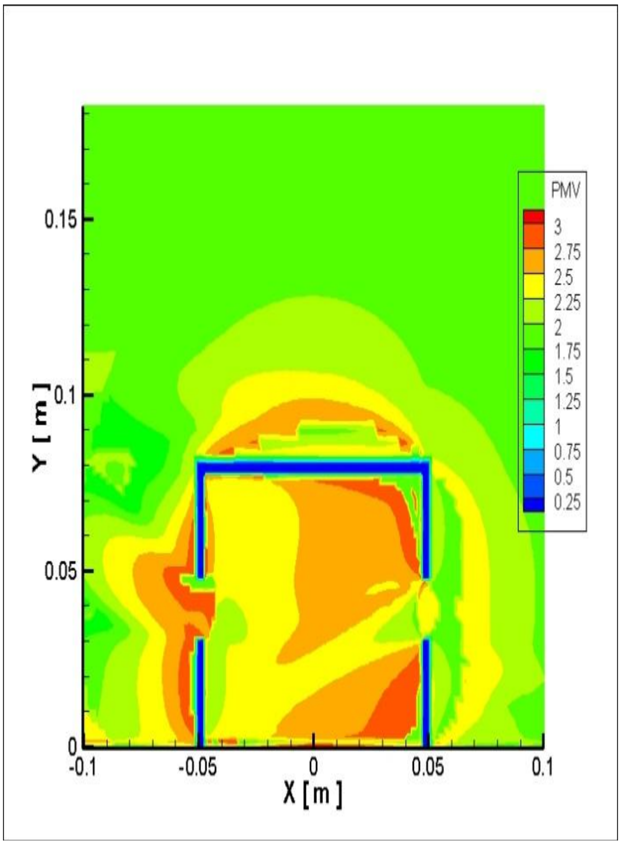
3.2. Thermal Comfort Analysis (PMV and PPD model)

For the analysis of the comfort zones across the naturally ventilated house, the Predicted Mean Vote and Predicted Percentage of Dissatisfaction model stands among the most recognized thermal comfort models. Here, the extended PMV model is used as it includes an expectancy factor for the better explanation with non-air-conditioned buildings in warmth regions [1].

The PMV model is a numeric scale varying from -3 to +3, which indicates the thermal comfort condition as per the given standard human living conditions. Here, negative values are considered as colder environment and positive values are considered as hotter environment. This model was originally developed by P. O. Fanger [1] and later adopted as an ISO standard. A mathematical model of the relationship between all the physiological and environmental factors is developed to show the results which can relate the sensational scale. As per the accepted standards by ASHRAE [7], for a human being, minimum requirement of PMV values lies as $-0.7<PMV<0.7$ for complete thermal comfort. For the value of PMV out of this range, it is suggested to have mechanical ventilation system.

The PPD model predicts the percentage of occupants that will be dissatisfied with the thermal conditions. It is a function of PMV, given that as PMV moves further from 0, or neutral, PPD increases. The maximum number of people dissatisfied with their comfort conditions is 100% and, as you can never please all of the people all of the time, the recommended acceptable PPD range for thermal comfort from ASHRAE 55 is less than 10% persons dissatisfied for an interior space.

Figure 6 shows the PMV and PPD contours for the simulated building under the weather conditions of the month of May. This contours are derived from calculating the mathematical model of PMV and PPD, considering and accounting all the thermal comfort factors, from the CFD analysis of the building model. The contour of PMV and PPD suggests that the most of the inside area of the building is having PMV values more than 2.5, as well as PPD values more than 85%. This values strongly suggests the dissatisfaction under the given climate conditions with natural ventilation.



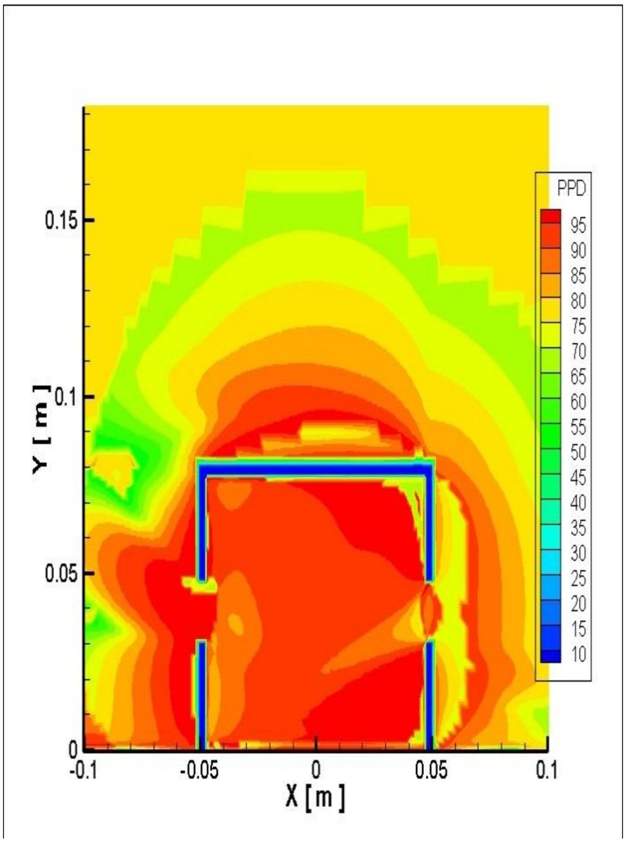


Figure 6. Predictive Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) contours from the computational results at the center plane of domain

IV. CONCLUSION

The numerical analysis presented in this paper shows the efficacy of the CFD tool for calculating the indoor air quality for the thermal comfort in normal working condition under warm summer weather conditions of Delhi. The contours of PMV model represents the requirement of the mechanical ventilation for certain areas, as the minimum requirement for the thermal comfort is 0.7>PMV>-0.7 [7]. The study can further be extended for the estimation of heating load or cooling load requirement under certain conditions like – presence of occupants, various appliances load and infiltration load. CFD analysis for thermal comfort can also be helpful in determining the most effective location for the mechanical ventilating appliances.

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