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CFD Analysis of CO_2 Concentration and Temperature Distribution in an Office Room Using Two Mechanical Ventilation Modes

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Abstract- The study simulated the airflow pattern, thermal comfort and occupational exposure to CO_2 under two ventilation modes using computational fluid dynamics (CFD). A wall supply diffuser was located at the floor level for the displacement ventilation case while the supply air diffuser was placed at the ceiling level for the mixing ventilation mode. The manikin served as a jet, exhaled air through the nostrils downward at an angle of 45 degrees below the horizontal line. The CO_2 species was modeled as a passive scalar transport convection-diffusion equation. From the result obtained, the mixing ventilation case showed a low level of CO_2 concentration than in the displacement ventilation case. Also, higher vertical temperature gradient was noticed in the displacement ventilation case as opposed to the mixing ventilation scenario. Lastly, the mixing ventilation case showed higher tendencies of local draft than displacement ventilation case.

Index Terms- CFD, CO_2 Dispersion, Displacement Ventilation, Mixing Ventilation, Thermal Comfort.

I. Introduction

Humans are the primary producers of CO_2 inside a building [1]. Over the years, in-situ measurement has been used as crucial tools in determining air distribution and airflow within an office space. However, due to the energy and time consuming process involved in taking readings at many locations, computational fluid dynamics have been recommended as an alternative approach in analyzing airflow and air distribution in an enclosed environment

Computational fluid dynamics has been extensively used as a method of studying indoor environment involving HVAC to recover results that may be difficult to obtain through measurements and in-situ-data collection.

According to [2], numerical analysis can be positively used to estimate the distribution of CO_2 exhaled by occupants in a room.

Note that in a ventilated room, two mechanical ventilation modes are widely used [3]. These are the mixing ventilation and displacement ventilation.

Reference [4], while investigating the diffusion characteristics of aerosol particles in a ventilated room, found out that particle concentration within the room for the displacement ventilation case is larger than observed in the mixing ventilation case.

Also, according to [3],for a mixing ventilation depending on the placement of the diffuser and exhaust grill, showed better result in terms of thermal comfort than the displacement ventilation scenario for an office space.

The aim in this study is to analyze the CO_2 distribution and thermal comfort of seated occupants within an office space. The aim was pursued with the following objectives:

1) Modelling the CFD case study
2) Analysing the distribution of airflow within the office space for the two ventilation modes
3) Comparing the result of the vertical temperature gradient within the breathing zone for the two ventilation modes.
4) Analysing and comparing the CO_2 dispersion within the office space for the two ventilation modes.
5) Analysing the level of occupant discomfort in terms of local draft for the two ventilation modes
6) Assessing the PPD and PD within the occupied zone for the two ventilation modes.

II. METHODOLOGY

The study investigates the thermal comfort and CO_2 spatial distribution in an enclosed office space using CFD simulation. The condition and the modelling of the spatial distribution of CO_2 in the office space have been done using SIMFLOW commercial CFD software.

In the study, the manikin in the CFD simulation for the exhalation process was based on the methodology adopted in [5]. The manikins extract which serves as a jet exhaled air through the nose downwards at an angle of approximately 45 degrees below the horizontal line.

According to equation below,

$$V_{exaust} = \frac{Q}{S} = \frac{\frac{Q}{\pi d^2}}{4}$$

Where Q = Flow rate = $8.5^{I}/_{m}$

The nostril of diameter 0.12mm exhales CO_2 at a velocity of 1.25m/s and at an angle of 45 degrees below the horizontal plane.

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Assuming the occupant is doing sedentary activity, the vertical component in both the Z axis and Y axis is 0.885m/s.

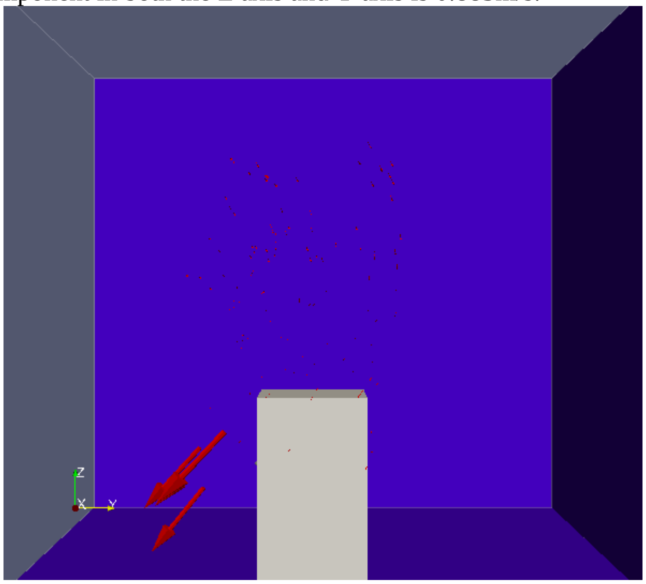

Figure 1: Velocity Vector for exhalation (CFD)

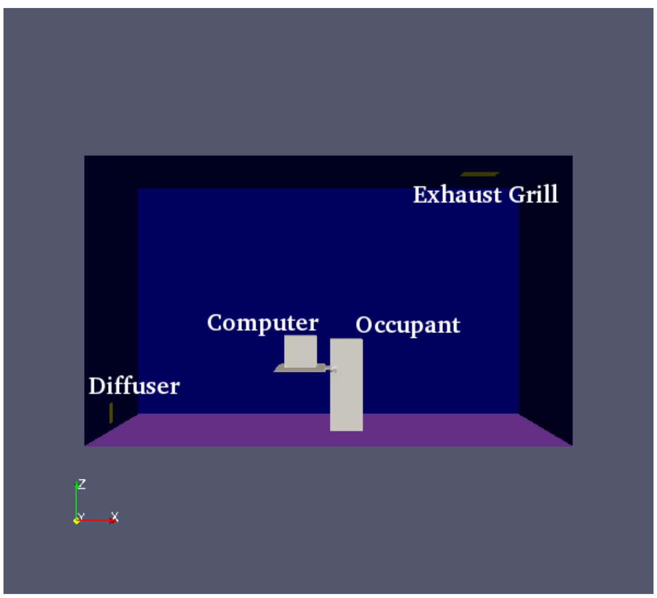

Figure 2: Room Layout for the displacement ventilation case

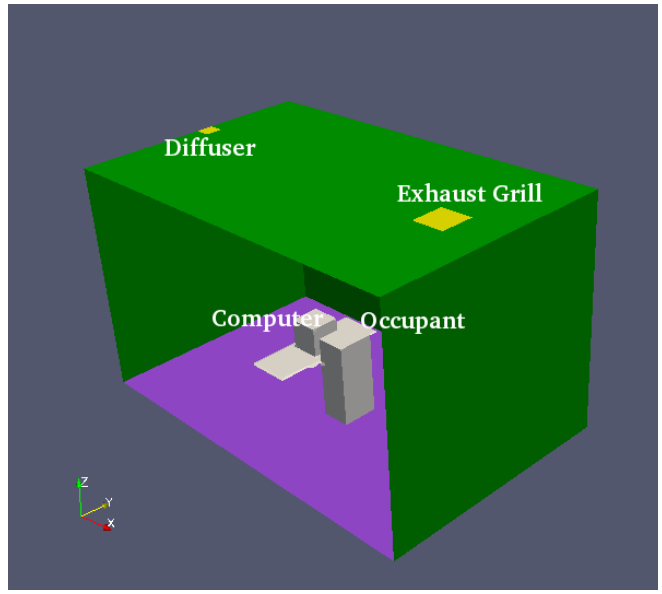

Figure 3: Room Layout for the mixing ventilation case

The layout of the room is presented in fig 1 and 2. The room is thermally isolated on the three sides and its base. For both the displacement and mixing ventilation case, the supply air temperature was constant at 19℃. The supply air velocity for the displacement and mixing ventilation case was 0.2m/s and 0.74m/s respectively. In both models, stale air leaves the room through the ceiling mounted grill.

The concentration of CO_2 species in the air was modelled as a passive scalar (φ) transport into the convection-diffusion equation in the form:

$$\partial\varphi\partial t + \nabla.(\cup\,\varphi) = \nabla.(D\nabla\varphi) + S\varphi$$

Where, $\cup$ is velocity obtained from the momentum equation, D is diffussity coefficient and $S\varphi$ is the source term.

The author made use of heat transfer and turbulent flow in fluid to determine the airflow and forced ventilation in the room. These physics solved the Navier Stokes Equation and continuity equation for air as well as convection-diffusion equation for heat.

Second order discritization scheme was used for the convective and viscous term of the flow. For the thermal comfort, buoyant simple foam compressible solver was used.

Many previous researches have made use of the RNG KE turbulence model to model the Reynolds stresses for this kind of simulation. Reference [6], investigated eight different turbulence models, from which he concluded that the RNG KE turbulence model provided more accurate result for the turbulence indoor airflow computation. For this research,

The RNG KE turbulence model was used.

Table 1: BOUNDARY CONDITION FOR HEAT SOURCE IN THE OFFICE

Heat source	Power(watts)
Occupant	75
Computer	40

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III. RESULT AND DISCUSSIONS

A. Flow Pattern

Fig 4 and 5 shows the distribution of air velocity at the ankle and head region for seated occupants.
Reference [7], recommends that air velocity on people should not normally exceed 0.15 to 0.2m/s depending on the air temperature and turbulent intensity.

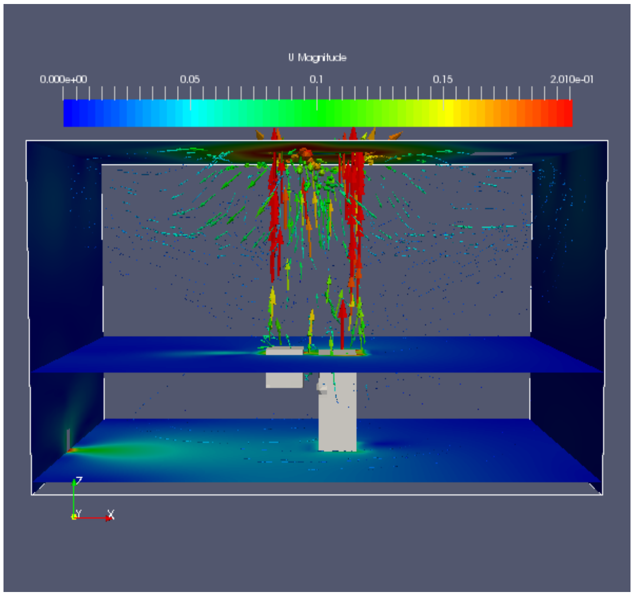

Figure 4: Velocity Magnitude for the displacement ventilation

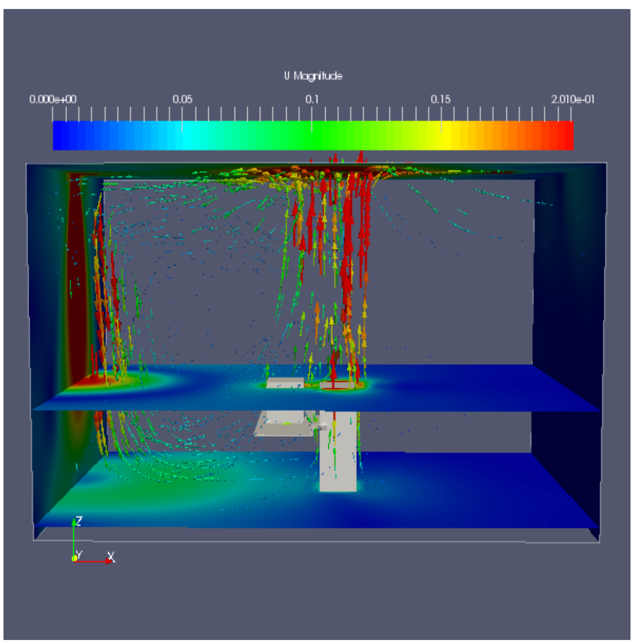

Figure 5: Velocity Magnitude for mixing ventilation

In the fig above, the red coloured surfaces on post processing slice view represents the regions with velocity magnitude greater than 0.2m/s where occupants within the office space may experience local draft as a result of the high air speed.
The two figures above illustrates that the local draft is considerably higher in the mixing ventilation than in the displacement ventilation case.

B. CO_2 Concentration Distribution

In reality, breathing of human beings is a periodical behaviour i.e. People have to inhale for a period of seconds before exhaling. However, in this study, only constant exhalation process was simulated.
A normal adult doing sedentary office work produces approximately $0.0051 {}^{l}/_{s}$ ($18 {}^{l}/_{h}$) of CO_2 during respiration.

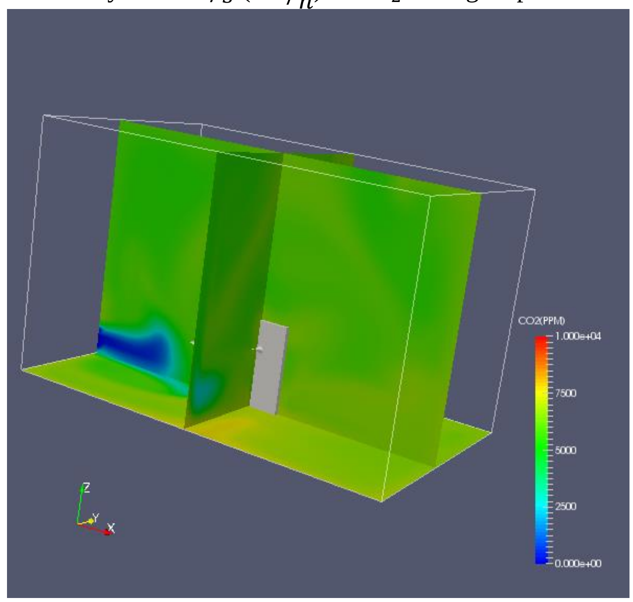

Figure 6: CO_2 Concentration for the displacement ventilation case

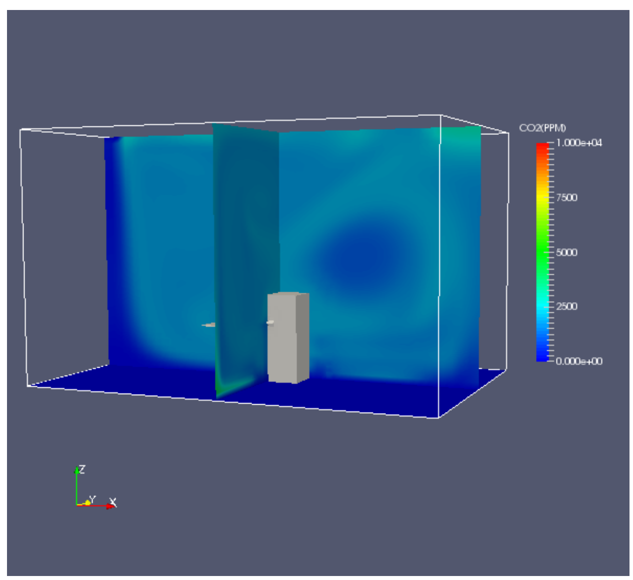

Figure 7: CO_2 Concentration for the mixing ventilation case

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According to [8], CO_2 concentrations below 1000ppm are recommended to avoid discomfort in form of drowsiness and headache.
As seen in fig 6 and 7, the CO_2 dispersion in the two ventilation mode are different.
There tend to be higher concentration of CO_2 in the displacement ventilation case than in the mixing ventilation case.
In the mixing ventilation case, a large portion of the office room recorded lower concentration of CO_2(below 1000ppm).unlike the displacement ventilation case where the CO_2 concentration in most part of the office space were as high as 5000-5500ppm.

C. Thermal Comfort

As shown in the fig below, in the displacement ventilation scenario, a vertical temperature gradient exists between the supply and extract grill respectively leading to higher temperature at ceiling level than in the mixing ventilation case.

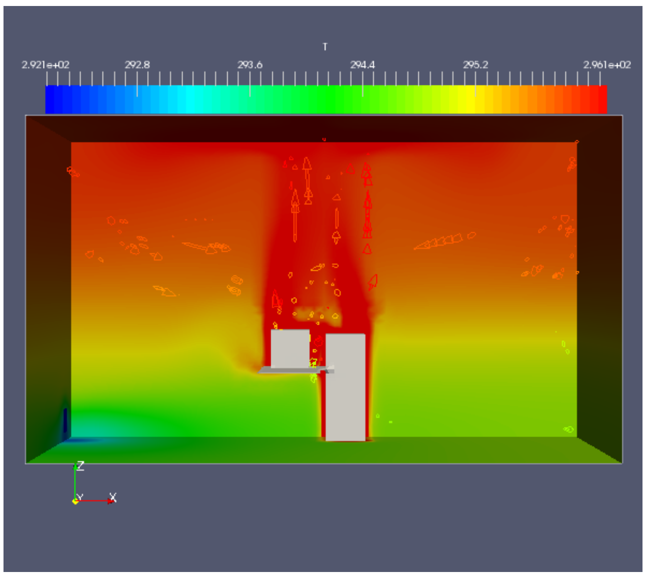

Figure 8: Temperature distribution for the displacement ventilation case

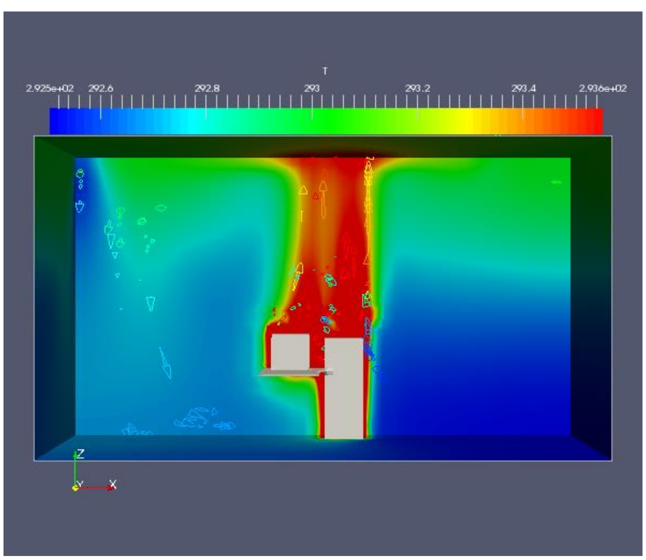

Figure 9: Temperature distribution for the mixing ventilation case

The maximum ankle to head temperature recorded in the displacement ventilation case is 22.085℃ and 20.9℃ respectively leading to a vertical temperature gradient of 1.185℃.
In the contour diagram (fig 9), it was observed that for the mixing ventilation case, the ankle and head region of the occupant within the occupied zone achieved uniform temperature (19.546℃) very close to the supply air temperature from the diffuser. This is because the heat source (occupant and computer) were continually diluted by the cold fresh air. Air in the room is fully mixed and therefore, air temperatures are uniform throughout the space.

According to the equation of percentage of dissatisfied people (PD) as stipulated in [7],

PD= (34-T) (u-0.05)$^{0.62}$(3.14+0.34uT_u)
Where T_u= 100(2K)$^{0.5}/u$ for PD>100%, PD=100%

The formula for calculating PPD can also be found in [7]:
PPD = 100-95$e^{(-0.03353pmv^4-0.2179pmv^2)(100\%)}$

The PMV (predicted mean vote) = $(0.303e^{-0.036m} + 0.028)L$
Where L = thermal load on the body, L= difference between heat production and heat loss to the actual environment.
M = Rate of metabolic heat production ($^W/_{m^2}$) = 58.15$^W/_{m^2}$

[7], also provides the mean radiant temperature equation for forced convection as follows:
T_r=$[(t_g + 273)^4 + \frac{1.1\times10^8 u^{0.6}}{\varepsilon d^{0.4}} \times (t_g - t_a)]^{0.25} - 273$
For a standard globe value of ε = 0.95 and d = 0.15m.
The metabolic rate of an occupant doing sedentary office activity is 1.2met. The author assumes that the occupant is wearing trousers and a long sleeve shirt and therefore his clothing level is 0.6.
If the assumed relative humidity is at 50%, then the predicted mean vote (PMV) for the displacement and mixing ventilation simulation is at -0.6 and -1.15 respectively.
The result predicted people dissatisfied shows that the probability of the occupant being dissatisfied with the office room temperature for the displacement and mixing ventilation case is 12.6% and 32.7% respectively, with the sensation of being cold.

IV. CONCLUSION

This paper evaluated the physical phenomenon of airflow, thermal comfort and CO_2 exposure in an office space using CFD method. Proper simulation of the nose geometry (exhalation) was modelled to study the transport of exhaled gas in the room.
The following conclusions were drawn based on the results of the visualization of the airflow pattern, temperature distribution and CO_2 dispersion:

[1].The concentration of CO_2 contamination within the displacement ventilation case is larger than in the mixing ventilation scenario.
[2].The displacement ventilation case showed higher vertical temperature gradient between the head and ankle region than observe in the mixing ventilation case.

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[3].Occupants in the mixing ventilation case have a higher tendency of experiencing local draft than in the displacement ventilation case.

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