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Indoor Air Quality and Outdoor Air Requirement for Personal Ventilation System in Office Spaces

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Abstract

The study presented in this paper is a continuation of Abdelmaksoud and Khalil's [1-2] studies on the occupant's thermal comfort in office spaces. That study was performed using the computational fluid dynamics (CFD) method and recommended the use of modern ventilation system that combines the effect of displacement ventilation and personal ventilation systems. This ventilation system provides an ideal thermal comfort for the occupant in the office. But, the thermal comfort is independent of the indoor air quality, which was not included in Abdelmaksoud and Khalil's study. Poor indoor air quality can induce health problems and lower the activity level. The carbon dioxide (CO_2) is used in the present study as an indicator of the air quality in the space. The CO_2 is emitted with human's respiration and correlates with the human metabolic activity. ASHRAE [3] recommends a maximum limit of 700 ppm differential between indoor and outdoor levels of CO_2 concentration.

In the present paper, we investigated the CO_2 concentration distribution around the occupant location in the office cubicle configuration that was presented in the earlier papers of Abdelmaksoud and Khalil [1-2]. The objectives were to: (1) investigate the CO_2 concentration level in the breathing zone of the human, and (2) recommend a minimum amount of outdoor air ventilation rate that maintains the CO_2 concentration in the breathing zone below the maximum allowable limit. To achieve these objectives, several CFD cases were studied and their results are presented in this paper.

Keywords - Indoor air quality; carbon dioxide; CFD; personal ventilation

1. Introduction

For an average person, a significant portion of the day is spent indoors, about 90 % [4], making indoor air quality (IAQ) an important health concern. The IAQ deals with the content of the interior air that could affect the health and comfort of the occupants in buildings. The IAQ is compromised by microbial contaminants (mold, bacteria), chemicals (such as carbon dioxide, radon), allergens, or any mass or energy stressor that can induce health effects. To improve the quality of indoor air, fresh air (minimum of 8.5 L/s per person) from the outdoor is introduced to the indoor environment according to ASHRAE standard [3] through ventilation systems. Either too much of fresh air (Over-ventilation) or too little of fresh air (Under-ventilation) in a building can be a problem. Over-ventilation results in higher energy usage and costs than necessary with appropriate ventilation and potentially increasing IAQ problems in warm, humid climates. Under-ventilation leads too poor air quality that can cause occupant discomfort and health problems.

In the present paper, we assume that the carbon dioxide (CO_2) is an indicator of the air quality in the space. The carbon dioxide is an indoor pollutant 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.. ASHRAE [3] recommended a maximum limit of 700 ppm differential between indoor and outdoor levels of CO_2 concentration. Also, ASHRAE [3] specified the rate of CO_2 generation from human byproduct respiration with the physical person activity. For office work, the human generates 0.3 L/min of CO_2 from total 9 L/min breathing rate or the CO_2 concentration (mole fraction) in the human respiration equals 0.033 L_{CO2}/L_a (or 33000 ppm). So, if the concentration of CO_2 in inhaled air is ~ 350 ppm then the concentration of CO_2 in exhaled air is ~ 100 times higher than in inhaled air [4].

The office configuration studied in Abdelmaksoud and Khalil [1-2] was chosen for investigating the CO_2 concentration in office spaces that use modern ventilation system (personal ventilation). In personal ventilation (PV) systems, the clean (fresh) outdoor air is directly supplied to the occupant's face so healthy environment is assured. Also, in PV systems, there is a potential of energy saving through reducing the amount of the outdoor air supplied to the space because there is no need to fill the zones far from the occupants with outdoor conditioned air. In the present study, we used the CFD tool to predict the CO_2 distribution in the studied domain (discussed later), which uses the PV system and to determine the minimum amount of outdoor air that doesn't exceed the ASHRAE limit of 700 ppm differential between indoor (in the breathing zone) and outdoor levels of CO_2 concentration. CO_2 concentrations in outdoor air typically range from 300 to 500 ppm [3]. Thus, if the CO_2 concentration in outdoor air is 400 ppm, then the maximum allowable CO_2 concentration in indoor air is 1100 ppm.

2. The Computational Model and Setup

A CFD study was carried out to investigate the CO_2 distribution around the occupants inside office spaces that use the modern PV systems. The office configuration that studied in Abdelmaksoud and Khalil [1-2] was selected for performing this CFD study. This office consists of eight cubicles; a part (one quarter) of that office is shown in Fig. 1, which shows two parallel cubicles (two seated persons per cubicle) with a 4 ft wide corridor. Each cubicle occupies 12 ft × 6 ft of the office floor area with 6.5 ft wall partition height, while the office has 10 ft ceiling height. Each half of a cubicle contains one seated person, computer, monitor, drawer, and table. In the CFD simulations, the seated person is facing the computer (normal position) and modeled as an assembly of blocks forming a head, torso, and two legs separated by a 6 inches gap. These blocks represent the typical surface area of a real human body, which is ~19.7 ft^2.

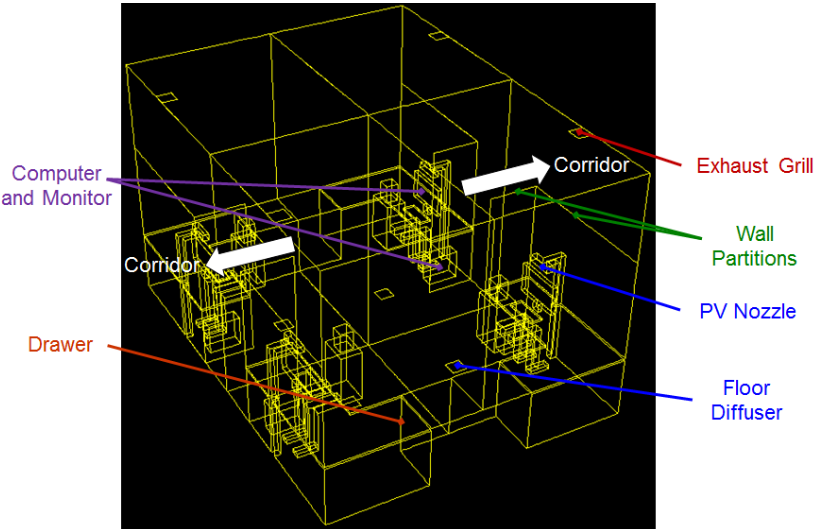

Fig. 1 Part of the office layout for the present study: 12 x 16 x 10 ft

Due to the symmetry in the office configuration shown in Fig. 1, it was suggested in the study of [1] to model only a quarter of that configuration (half of a cubicle + half of the corridor width) so the model domain size becomes 6 × 8 ×10 ft; this resulted in decreasing the CFD computational time significantly. This modeling was performed via imposing three symmetry boundary conditions on the computational domain, which is shown in Fig. 2. The grid generation software GAMBIT 2.4.6 [5] was used to generate the three-dimensional mesh of the domain shown in Fig. 2. The resulted total number of grid cells (essentially structured) in the domain is ~1,350,000. More details such as the grid cells distribution in the domain and the boundary conditions for the seated person’s body, computer and monitor can be found in the earlier papers of Abdelmaksoud and Khalil [1-2].

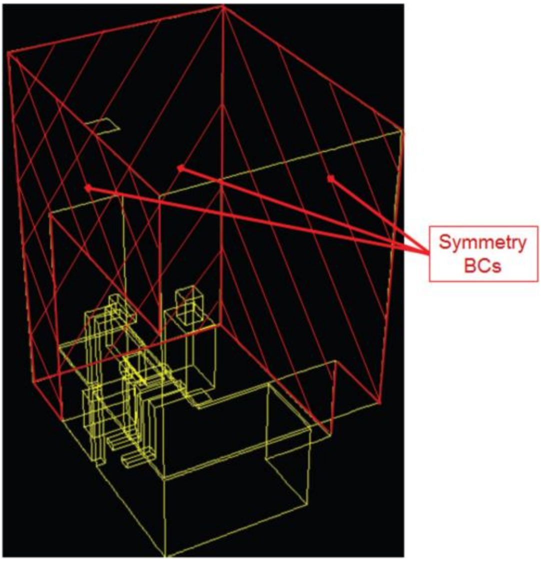

Fig. 2 The CFD computational domain for the present study: 6 x 8 x 10 ft

The previous study by Abdelmaksoud and Khalil [1] investigated the flow and thermal fields in the described office configuration under several ventilation systems (displacement ventilation, PV, and combination of displacement ventilation and PV). The analysis of the CFD results in Abdelmaksoud and Khalil's [1] study showed that the ideal ventilation case (ideal thermal comfort, or predicted mean vote PMV ~ 0) is a combination of displacement ventilation and PV system. This ideal case (for one seated person) required 65% of the total airflow rate (~13 L/s) of supply air from the floor diffuser and 35% of the total airflow rate (~7 L/s) of supply air from the PV nozzle. Note that the thermal comfort index (predicted mean vote, PMV, developed by Fanger [6]) presented in the previous study [1] is independent of the indoor air quality. Based on the ideal design setup (13 L/s and 7 L/s of airflow rate from the floor diffuser and the PV nozzle respectively) suggested in the previous study [1], we will investigate the effect of the outdoor air percentage in the supply air on the CO_2 distribution around the seated person in the office described in Fig. 1. Several CFD cases were studied and presented in this paper to reveal the case conditions that provides the minimum amount of outdoor air that doesn't exceed the ASHRAE limit of 700 ppm differential between indoor (in the breathing zone) and outdoor levels of CO_2 concentration. Thus, if the CO_2 concentration in outdoor air is 400 ppm, then the maximum allowable CO_2 concentration in indoor air is 1100 ppm.

3. The CFD Cases

Starting from the ideal case design setup that was introduced in Abdelmaksoud and Khalil's study [1] and briefly described in the previous section, we will investigate the CO_2 distribution around the occupant's body at different amounts of CO_2 concentration in the supply air from the PV nozzle and the floor diffuser. Four CFD cases were investigated and presented in this paper. The baseline case, Case 1, represents a total fresh (outdoor) air design where the CO_2 concentration in the supply air from both the PV nozzle and the floor diffuser is 400 ppm. The remaining three cases use 500, 600 and 700 ppm which mean that there is mixing between the return air and the outdoor air before passing the components of the air conditioning (AC) machine. Therefore, the highest AC energy consumption is found in Case 1 while the lowest AC energy consumption is found in Case 4. Table 1 summarizes the CO_2 concentration boundary condition in the four cases.

Table 1. CO_2 concentration boundary condition in the four CFD cases

Case	PV nozzle and floor diffuser CO_2 concentration (ppm)
1	400*
2	500
3	600
4	700

* The 400 ppm represents a total fresh air supply design.

In the four CFD cases, the seated person was modeled with constant breathing rate of 9 L/min that has a volumetric CO_2 concentration of 0.033 L_{CO2}/L_a (or 33000 ppm). Therefore, the highest CO_2 concentration in the CFD results will appear around the person's face while the lowest CO_2 concentration will appear around the air supply locations.

All the CFD simulations on the domain shown in Fig. 2 were performed using a commercial CFD software package, ANSYS Fluent 14 [7]. The flow was assumed incompressible, and the Reynolds-averaged Navier Stokes equations were solved with the SIMPLE algorithm. All convective transport terms were discretized using a second-order-accurate upwind scheme, while the diffusion terms were discretized using a second-order-accurate central-difference scheme. Pressure interpolation was achieved with a second-order-accurate scheme. The widely accepted two-equation standard k-ε turbulence model, coupled with standard wall functions, was employed. Buoyancy was modeled using the incompressible ideal gas method, which treats the air density as a function of the local temperature and the operating pressure field (not on the local relative pressure) using the ideal gas law for an incompressible flow.

4. The CFD Results and Discussions

4.1 CO_2 Concentration Ratio

This section will firstly discuss the generated results from the four CFD cases described in the previous section. The results here are presented in a dimensionless form, CO_2 concentration ratio (CR), which is defined as

$$CR = 100\left[1 - \frac{C_{outdoor}}{C}\right] \tag{1}$$

where $C_{outdoor}$ is the CO_2 concentration in the outdoor air, which is assumed to be 400 ppm in the current simulations and C is the predicted CO_2 concentration in any location inside the studied domain. The value of CR ranges from 0 to 100. The lower the CR is, the cleaner (lower CO_2 concentration) the air in the domain. For example, a zero value of CR will appear when the outdoor air is supplied to the domain (total fresh air design) while the value of 100 will appear at the front of the person's face because of the highest CO_2 concentration supplied from the person's mouth.

Fig. 3 shows the CR results from the four CFD cases in a plane that bisecting the person's body. Because of the total fresh air design, Case 1 shows the lowest CR values around the person's body. The CR values increases above the person's head because of the mixing between the supply air and the exhaled air (high CO_2 concentration source) from the person's mouth and rises up due to buoyancy to the exhaust grill. As the CO_2 concentration increases in the supply air, Cases 2 to 4, the CR values gradually increases in the entire domain. Now, we need to estimate the maximum CO_2 concentration that can be supplied to the domain while maintaining the CO_2 concentration in the breathing zone just below the ASHRAE limit.

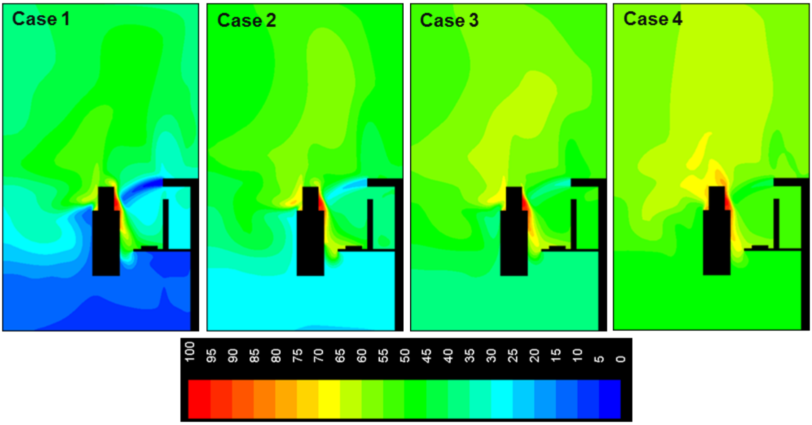

Fig. 3 The concentration ratio (CR) contours in a plane bisecting the person's body

4.2 Breathing Zone CO_2 Concentration

As shown in Fig. 3, as the CO_2 concentration in the supply air increases, the CO_2 concentration in the entire domain increases. Thus, the CO_2 concentration in the breathing zone (BZ) increases. The BZ is defined as the region within an occupied space between planes 3 and 72 inches above the floor and more than 24 inch from the walls [3]. Based on this definition, the dashed rectangle in Fig. 4 represents the BZ location in the studied domain.

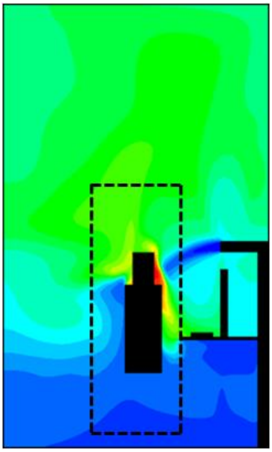

Fig. 4 The breathing zone (BZ) location in the studied domain

Table 2 lists the average predicted CO_2 concentration in the BZ region in each case. Two observations can be drawn from that table: (1) all the studied four cases didn't exceed the ASHRAE limit (1100 ppm in the BZ) so we still have opportunity to save more energy via increasing the supply CO_2 concentration more than the 700 ppm in Case 4, and (2) there is a linear variation between the supply and the BZ CO_2 concentrations (i.e., every 100 ppm increase in supply CO_2 concentration results in nearly a 100 ppm increase in the BZ CO_2 concentration).

Table 2. Breathing zone (BZ) CO_2 concentration in the four CFD cases

Case	Supply CO_2 concentration (ppm)	BZ CO_2 concentration (ppm)
1	400	681
2	500	783
3	600	881
4	700	982

Fig. 5 shows the maximum allowable CO_2 concentration that can be supplied to the domain. This figure shows that we can increase the CO_2

concentration in the supply air up to ~ 800 ppm, which doesn't exceed the ASHRAE limit in the BZ location.

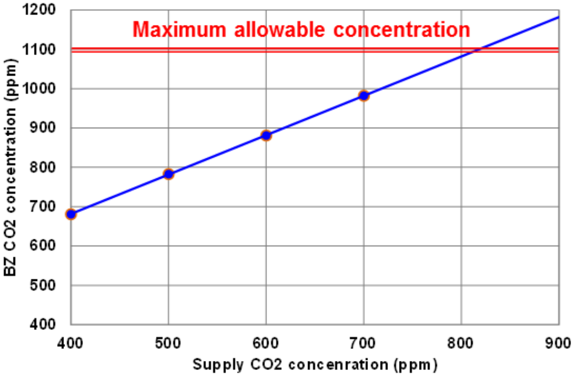

Fig. 5 The supply CO_2 concentration vs. the predicted beathing zone (BZ) CO_2 concentration

4.3 Minimum Outdoor Air Requirement

In this section, we estimate the amount of the outdoor airflow rate in each CFD case and hence we estimate the minimum outdoor airflow rate that reaches the ASHRAE limit. In each CFD case, we estimated the amount of outdoor airflow rate (ventilation rate) as a percentage of the total airflow rate using the following equation [8]

$$\text{Outdoor air } (\%) = 100\left[\frac{C_{supply} - C_{return}}{C_{outdoor} - C_{return}}\right] \tag{2}$$

where C_{supply} is the CO_2 concentration in the supply air and C_{return} is the average predicted CO_2 concentration in the exhaust grill. Note, in each CFD case, the C_{supply} value is the same in both the PV nozzle and the floor diffuser because we assumed that the supply airflow comes from the same AC duct line.

The amount of outdoor airflow rate entering the space can be calculated by multiplying the total airflow rate (20 L/s per the seated person) by the outdoor air (%) as follow

$$\text{Outdoor air (L/s)} = (\text{outdoor air } (\%)/100) \times \text{total airflow (L/s)} \tag{3}$$

Using Equations 2 and 3, Table 3 lists the calculated amount of outdoor airflow rate (in L/s per person) entering the space in each CFD case. Using the results shown in Fig. 5 and in Table 3, summarized in Fig. 6, we estimated that a ~ 8 L/s per person is the minimum amount of outdoor air required for ventilating the office space shown in Fig. 1. This estimated value nearly agrees with the ASHRAE standard [3], which specified a minimum of 8.5 L/s per person ventilation rate.

Table 3. The outdoor airflow rate in the four CFD cases

Case	Supply CO_2 (ppm)	Return CO_2 (ppm)	Outdoor air (%)	Outdoor air (L/s)
1	400	681	100	20
2	500	788	74	15
3	600	880	58	12
4	700	985	49	10

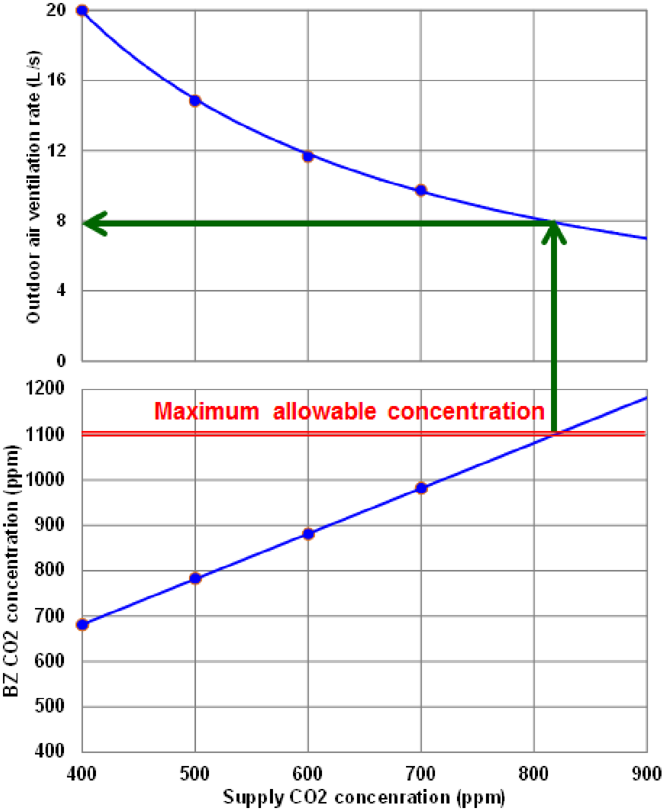

Fig. 6 Estimation of the minimum amount of outdoor air in L/s per person

5. Summary and Conclusions

CFD simulations were carried out to study the indoor air quality and estimate the minimum ventilation rate required for ventilating an office space that uses personal ventilation system. Four CFD cases with four values (400, 500, 600 and 700 ppm) of CO_2 concentration in the supply air were investigated to predict the average CO_2 concentration in the breathing zone. The CFD case with 400 ppm CO_2 concentration represents a ventilation design with total fresh (outdoor) air while the remaining three CFD cases represent ventilation designs with mixing between the return air and the outdoor air. The analysis of the CFD results showed that: (1) every 100 ppm increase in the supply CO_2 concentration results in nearly a 100 ppm increase in the breathing zone CO_2 concentration, and (2) in order to not exceed the ASHRAE limit (1100 ppm of CO_2 concentration in the breathing zone), a minimum of ~ 8 L/s per person of outdoor air is required for ventilating the office.

Acknowledgment

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