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Investigating Formaldehyde Concentration and Distribution of New Office Building

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Abstract

Air pollution is a major environmental risk to health. A new building usually faces problems with indoor air pollutants. Formaldehyde is a common contaminant emitted from decoration materials, such as particleboards and wood-based materials. Higher formaldehyde concentration can affect human health problems, and discomfort and reduce productivity. The purpose of this study is to investigate formaldehyde concentration and distribution in a new and full air-conditioning office at a dimension of 7.3m x 5.8m x 2.9m. The formaldehyde concentration values were investigated through field measurements and compared to the limits stated in the Occupational Safety and Health Act standard. Meanwhile, the formaldehyde distribution in the new office was predicted through the CFD simulation. This study built a CFD model of the Dean's office, validated it using published experimental data in the literature, and applied it to open-door situations under different ventilation schemes. The result shows that formaldehyde concentration exceeds the maximum limit of OSHA standard and the zone under the ceiling cassette air condition experiences the highest concentration zone compared to other zones. A healthy environment in the office can be achieved by reducing the formaldehyde concentration level through effective formaldehyde distribution.

Discipline: Thermal Engineering, Build Environment, Building Simulation

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1 Introduction

In the current decade, indoor air pollution is one of the most important interesting research issues due to the fast developments. The impacts of development have caused indirect effects such as indoor air pollution inside the building itself. Increasing awareness and controlling common indoor pollutants can assist to reduce people's risk of indoor health concerns (Mahima et al., 2015).

Humans spend most of their time indoors, and most of the world's population lives in urban areas and works in an office environment. Therefore, office buildings need to create good indoor air quality performance for occupants because an office environment has a high level of influence on its occupant's productivity (Monika et al., 2012). Thus, there is a need to investigate the quality of the indoor workplace environment. This study investigates one of the common contaminants in the office which is formaldehyde.

Formaldehyde is known as one of the main indoor air pollutants (Tunga, 2019). Indoor air pollution caused by formaldehyde concentration can result in serious respiratory diseases, eye irritation, headache, asthma, as well as degenerative, inflammatory, and hyperplastic changes of the nasal mucosa (Lim et al., 2011). To control formaldehyde pollution, the influencing factors of formaldehyde concentration are examined such as ventilation modes, office materials, air temperature, and relative humidity which positively affect the formaldehyde concentration (Daocong et al., 2020).

The Industrial Code of Practise on Indoor Air Quality (ICOP) (2010) issued by the Department of Occupational Safety and Health Malaysia stated the list of indoor air contaminants and the acceptable limits (Department of Occupational Safety and Health (DOSH) Malaysia, 2010). Prior to maintaining good indoor air quality, the acceptable limit of each indoor air contaminant must comply. The characteristics of good indoor air quality include the distribution of adequate ventilation air, control of airborne contaminants, and maintenance of acceptable temperature and relative humidity (Norhidayah et al., 2013).

The main objective of this research is to investigate formaldehyde concentration and distribution in the Dean's office at the new building of the Faculty of Mechanical Engineering in Johor Bahru, Malaysia to help reduce indoor air pollutants inside the Dean's Office. Sub-objectives related to the main objective are also created. The first sub-objective is to measure Formaldehyde concentration in the Dean's Office through field measurement. The second sub-objective is to predict Formaldehyde distribution within the Dean's Office through Computational fluid dynamics simulation. Computational fluid CFD is a powerful tool for understanding the airflow characteristic and contaminant concentration distribution within an indoor space. The third sub-objective is to examine the effect of the open door on the Formaldehyde concentration level. The research focuses on studying the strategy to improve the level of Formaldehyde concentration in the Dean's office at the new building, Faculty of Mechanical Engineering in Johor Bahru, Malaysia. The area of research is indoor air pollution in the selected building. Moreover, the physical characteristics of this study are included in the framework of the study.

2 Literature Review

2.1 CFD Study on Formaldehyde Concentration Distribution

In 2013, Zhuang et al. demonstrated a simulation method to investigate formaldehyde distribution in a typical office room under different furniture layouts and ventilation schemes. The simulation results of twelve cases show that furniture layout is an important factor in indoor airflow and temperature distribution. The quality of air in the breathing zone can be improved by adjusting the furniture layout without making any changes to the ventilation system.

2.2 Indoor Air Quality Approaches for Formaldehyde Removal

The general method for formaldehyde removal is by increasing the outdoor airflow rate using mechanical ventilation systems (Zhang et al., 2022) and using physical (Batani et al., 2010) or chemical-based air purification systems (Malayeri et al., 2021). Since 2004, ASHRAE considered the contribution of human and building-related pollution in determining the minimum outdoor ventilation rate. An approach that can be taken to achieve acceptable air quality indoors is to determine the ventilation rate based on pollutants that cause adverse health problems, such as formaldehyde contaminants. Applying a higher ventilation rate can reduce indoor air pollutants concentration; however, it consumes more energy (Zhuang et al., 2014). Therefore, a combined approach of mechanical ventilation and air purification system is the optimal method to provide a healthy indoor air environment.

Passive removal materials (PRMs) have received attention in improving indoor air quality. There are different types of PRMs such as ceiling tiles, wallboards, wallpapers, paint, and flooring (Bahri et al., 2018). PRMs can be classified into photocatalytic oxidative-based passive removal materials (PCO-PRMs) and sorptive-based passive removal materials (S-PRMs) (Bahri et al., 2019). Since PCO-PRMs can make a variety of hazardous by-products, the application of S-PRMs is of more interest in capturing indoor air pollutants.

3 Method

3.1 Description of Dean's Office

The investigation was carried out in the Dean's office at the new building, Faculty of Mechanical Engineering, the University of Technology Malaysia at Johor Bahru, Malaysia. This building has been operating for two years during the investigation. The dimension of the office is 7.3m x 5.8m x 2.9m. This office is equipped with two units of ceiling cassette air conditioning that can control the air temperature and air velocity. Every unit of ceiling cassette air conditioning has 4 units of 380mm x 90mm rectangular supply air diffuser and one unit of 305mm x 305mm square exhaust air diffuser located at the ceiling. Figure 1 below shows the 3D model of the Dean's office. During a site visit to the Dean's office, the doors and windows were closed.

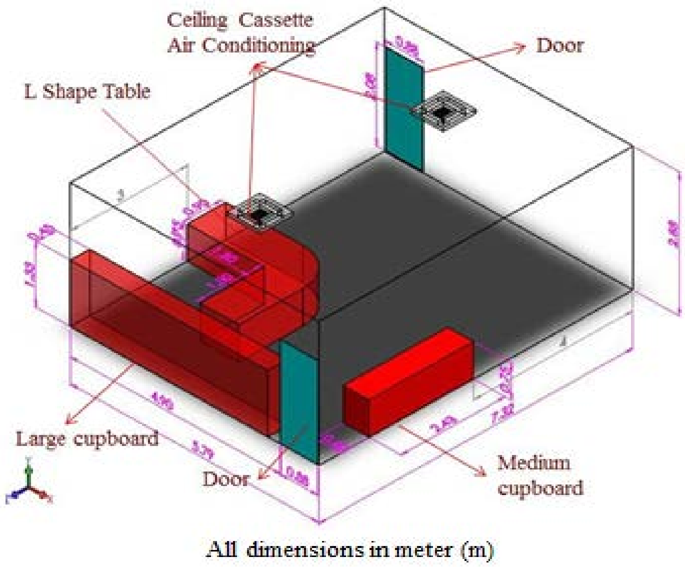


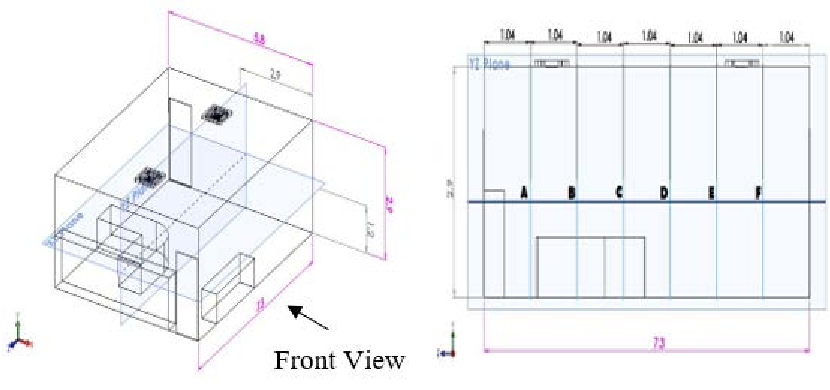
Figure 1: 3D model of the Dean's office (created by authors).

3.2 Field Measurement and Instrumentation

The dimensions of the various important features of the office are measured from the actual site and these values have been implemented in the simulation model. There are three purposes to conduct field measurements:

- To quantify Formaldehyde concentration in the Dean's Office
- To obtain the boundary condition used in CFD simulation
- To validate the CFD simulation result.

The formaldehyde concentration was measured inside the Dean's office. The experimental procedure and result of formaldehyde concentration have been published (Nor Azirah et al., 2022). Measurement was taken at six locations inside the Dean's office. The measuring instruments were placed at a height of 1.2m from the floor. The sampling points were placed at the occupant's breathing level which is 1.2 m above floor level. The data were conducted during actual working conditions. The reading of formaldehyde concentration was taken in 30 minutes. One minute is equal to one number of samples. Figure 2 shows the six sampling points for taking Formaldehyde concentration readings.



(a) (b)

All dimensions are in meter (m)

Figure 2: The six sampling points for taking Formaldehyde concentration reading (Nor Azirah et al., 2022).

The instruments used in conducting the field measurement are Bacharach's IEQ Chek (IEQ Chek) and Digital anemometer (*VICTOR 816B*). Bacharach's IEQ Chek (*IEQ Chek*) is used to determine the formaldehyde concentration in the Dean's office. The percentage error of IEQ Chek is ±2% over range. Meanwhile, a digital anemometer (*VICTOR 816B*) is used to determine the velocity at the supply and exhaust air diffuser. The percentage error of this device is less than the ±5% range.

The formaldehyde concentration data were compared with Occupational Safety and Health Act (OSHA) standard. The maximum limit for formaldehyde concentration by OSHA standard is 0.1 ppm.

3.3 CFD Simulation

A steady-state solver of finite difference based is used to solve the system of governing equations. The governing equations consisting of the conservation of mass, momentum, and species for steady-state conditions are solved iteratively.

- The mass conservation equation:

$$,\nabla.(\rho\,\vec{v}\,) = 0 \qquad (1),$$

- The momentum conservation equation:

$$\nabla.(\rho\,\vec{v}\;\vec{v}\,) = -\nabla\rho + \nabla.\left(\underline{\tau}\right) + \rho\,\vec{g} \qquad (2),$$

where ρ is the static pressure, $\rho\,\vec{g}$ is the gravitational body force, $\underline{\tau}$ is the stress tensor defined as

$$\underline{\tau} = \mu\left[\left(\nabla.\vec{v} + \nabla\,\vec{v}^{\,T}\right) - \frac{2}{3}\nabla.\vec{v}\,I\right] \qquad (3),$$

where μ is the molecular viscosity, I is the unit tensor, and the second term on the right-hand side is the effect of volume dilation.

- The species transport equation:

$$\nabla.(\rho\,\vec{v}\,Y_i) = -\nabla.\underline{J_i} \qquad (4),$$

where Y_i is the local mass fraction of each species i and $\underline{J_i}$ is the diffusion flux of species i, which arises due to concentration gradients.

The general form of transportation equations of k and ε which are derived from Navier-Stokes equations are as follows:

k - equation:

$$\frac{Dk}{Dt} = \frac{1}{\rho}\frac{\partial}{\partial x_j}\left[\left(\frac{\mu_t}{\sigma_k} + \mu\right)\frac{\partial k}{\partial x_j}\right] + \frac{\mu_t}{\rho}\frac{\partial U_i}{\partial x_j}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_i}{\partial x_i}\right) + \frac{\beta}{\rho C_p}\frac{\mu_t}{\sigma_H}\frac{\partial H}{\partial x_i}g_i - \varepsilon \qquad (5),$$

ε – equation:

$$\frac{D\varepsilon}{Dt} = \frac{1}{\rho}\frac{\partial}{\partial x_j}\left[\left(\frac{\mu_t}{\sigma_\varepsilon} + \mu\right)\frac{\partial \varepsilon}{\partial x_j}\right] + S_\varepsilon \qquad (6),$$

where

$$S_\varepsilon = C_1 \frac{\mu_t}{\rho} \frac{\varepsilon}{k} \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_i}{\partial x_i} \right) \frac{\partial U_i}{\partial x_j} - C_2 \frac{\varepsilon^2}{k} + C_3 \frac{\beta}{\rho C_p} \frac{\varepsilon}{k} \frac{\mu_t}{\sigma_H} \frac{\partial H}{\partial x_i} g_i \quad (7),$$

each modified k-ε model is concentrated on the selection of a set of turbulence parameters such as C_μ, C_1, C_2 *and* C_3.

3.3.1 Mesh Model

The main consideration of grid generation is the accuracy of the numerical solver in modeling the Formaldehyde distribution profile. In the selection of a grid or a mesh type for the model, the setup time issue is the most considerable item. The creation of mesh using triangular and tetrahedral elements resulted in fewer cells as compared to the equivalent mesh consisting of hexahedral elements. A greater number of elements requires more computational time. Hence, it enhances the setup time and reduces the computational time of iteration until an acceptable convergence is attained. Table 1 shows the detailed mesh of every item in the model.

Table 1: Detail description of mesh in the geometry.

Description	Type of Mesh	Type of element	No. of elements
Supply air diffuser	Face	Triangular	102
Exhaust air diffuser	Face	Triangular	143
Door	Face	Triangular	217
Wall and floor	Face	Triangular	2057
Interior Office	Body	Tetrahedral	2567

The skewness method can measure mesh element quality. The result of Skewness for the Dean's office modeling shows the maximum value is 0.76, which is in the range of good condition of mesh element quality. Figure 3 shows the result of meshing for the geometry of the Dean's Office.

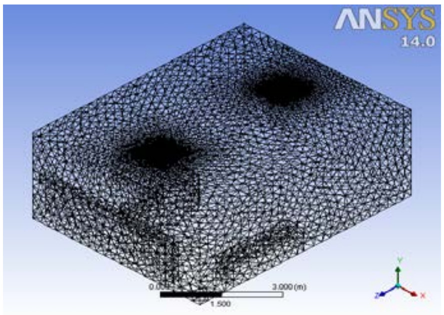


Figure 3: Mesh geometry of Dean's Office (created by authors).

3.3.2 Boundary Condition

The accuracy of CFD simulations strongly depends on the appropriate setting of boundary conditions. In the modeling of Formaldehyde distribution under steady-state conditions, the specific conditions of the source term must be defined. A source of Formaldehyde starts at the supply air diffuser due to the recirculating ventilation system. For the re-circulated ventilation system, the inlet is interrelated with the outlet closely. A fraction of contaminated air is exhausted by the outlet and mixed with a ratio of fresh air. After the mixing process, it recirculates in the room as an intake of air.

The cupboard and table in the geometry are only to show that the real environment is not affected by the formaldehyde concentration since the emission rate from the table and cupboard achieves an equilibrium state, which means formaldehyde reaction as its forward and reverse reactions occur at equal rates so that the concentration of the reactants and products does not change with time.

The office wall, floor, and door are no-slip boundary conditions being applied which are also assumed as adiabatic. The details of boundary conditions are listed in Table 2.

Table 2: Boundary Conditions for Dean's office.

Part of the Computational Domain	Boundary Condition	Type	Value
Door	Wall	Adiabatic	-
Wall and floor	Wall	Adiabatic	-
Supply air diffuser	Velocity Inlet	Velocity	3.8 m/s
		Formaldehyde mass fraction	0.0000004
Exhaust air diffuser	Velocity Inlet	Velocity	-1.6 m/s

The material of the mixture type formaldehyde-air is selected in the specific model. The properties of the mixture material are shown in Table 3.

Table 3: The properties of formaldehyde-air.

Type	Value	Unit
Density	Incompressible-ideal gas	kg/m^3
Specific Heat, C_p	Mixing law	J/kg.K
Thermal Conductivity	0.0454	W/m.K
Viscosity	1.72×10^{-05}	kg/m.s

3.3.3 CFD Simulation Setup

Among various turbulent models, the k-ε model is the most widely-used engineering turbulent model as it is robust, economical, and reasonably accurate for a wide range of airflow conditions (Jaw. et al., 1998). The Renormalization Group (RNG) k-ε was selected as the turbulence model, while SIMPLE was used as the pressure-velocity coupling algorithm. The discretization scheme was selected as a second-order upwind scheme for momentum, turbulence, and species chosen. In this study, CFD modeling was carried out in Ansys Fluent, a steady-state model to study the formaldehyde distribution.

The simulation was performed to predict formaldehyde distribution inside the Dean's office. The result of contaminants concentration is shown in mass fraction but in this analysis, the formaldehyde concentration is required in a unit of ppm. As a result, CFD software needs to define a new unit for concentration. The expression of concentration for converting mass fraction to ppm is formulated as below:

$$Concentration_{ppm} = Concentration_{mass\ fraction}\ x\ 10^{6} \quad (8),$$

3.3.4 Validation

To validate the simulation result, the graph of Formaldehyde concentration for both results (measurement and simulation) versus the sampling points selected in the Dean's Office will calculate the percentage difference between the simulation and measurement result. According to the ASHRAE Standard, the maximum acceptance percentage difference is less than 25% between the measurement and simulation results.

3.4 Parametric Study

The choice of parametric study must be considered carefully to ensure an acceptable value of Formaldehyde concentration, which is investigated by CFD simulation in this study. The parametric study allows for the varying geometry and boundary conditions that most influence the results. The varying geometry and boundary conditions can determine the best design option and configuration for the acceptable value of Formaldehyde concentration.

According to Rivas et al. (2022), increasing ventilation helps to decrease contaminants concentration. In this study, the open door is selected as a parametric study due to the open door as a function of natural ventilation. The boundary condition selected at the door is a pressure outlet, in which flow can exit through the door. The type of pressure at the door is the pressure gauge and the value is 0 Pa.

The observations on the parametric study are Formaldehyde distribution and concentration. The Formaldehyde concentration of open-door conditions is compared with the Formaldehyde concentration of the actual environment. The purpose of the comparison is to know if the result of the new environment office affects the Formaldehyde concentration in the Dean's Office.

4 Result and Discussion

4.1 Field Measurement

4.1.1 Formaldehyde Concentration

Measurements were taken at 6 locations in the Dean's office. Every location consists of 30 samples for formaldehyde concentration measurements. Table 4 below illustrates the value of formaldehyde concentration versus the number of samples for locations A to F. It can be seen from the data in Table 4 that the maximum value is at location A with about 0.24 ppm and the minimum value is at location F with about 0.21 ppm. The formaldehyde concentration for both locations exceeds the maximum limit of the OSHA standard which is 0.1 ppm. The main indoor formaldehyde sources are wood-based building materials such as laminate wood flooring, furniture and decorative materials which are composed of artificial boards like density boards, particleboard and lumber cores (Huang et al., 2022). The highest formaldehyde concentration is recorded at location A with about 0.23 ppm to 0.24 ppm. Location A is observed to have a high concentration value of formaldehyde concentration due to its proximity to furniture made from wood-based materials such as tables and cupboards (Nor Azirah et al., 2022). The occupants standing at 1.2 m from the floor are exposed to a high level of formaldehyde concentration.

Table 4: Formaldehyde concentration versus number of samples for six locations.

No. of Sample	OSHA Limit (ppm)	Location					
		A	B	C	D	E	F
1	0.1	0.24	0.23	0.22	0.22	0.22	0.21
2	0.1	0.24	0.22	0.23	0.23	0.23	0.21
3	0.1	0.23	0.22	0.22	0.22	0.22	0.21
4	0.1	0.24	0.22	0.23	0.22	0.22	0.21
5	0.1	0.23	0.22	0.23	0.23	0.22	0.21
6	0.1	0.24	0.23	0.23	0.23	0.22	0.21
7	0.1	0.24	0.22	0.22	0.23	0.22	0.21
8	0.1	0.24	0.23	0.23	0.23	0.23	0.21
9	0.1	0.24	0.22	0.23	0.22	0.22	0.21
10	0.1	0.24	0.23	0.23	0.23	0.22	0.21
11	0.1	0.23	0.22	0.22	0.22	0.22	0.21
12	0.1	0.24	0.23	0.22	0.22	0.22	0.21
13	0.1	0.24	0.22	0.23	0.22	0.22	0.21
14	0.1	0.23	0.23	0.22	0.23	0.22	0.21
15	0.1	0.23	0.23	0.22	0.23	0.23	0.21
16	0.1	0.24	0.23	0.22	0.23	0.22	0.21
17	0.1	0.23	0.23	0.22	0.22	0.22	0.21
18	0.1	0.23	0.23	0.22	0.22	0.22	0.21
19	0.1	0.23	0.23	0.23	0.23	0.22	0.21
20	0.1	0.23	0.23	0.23	0.23	0.22	0.21
21	0.1	0.24	0.23	0.23	0.22	0.22	0.21
22	0.1	0.23	0.23	0.23	0.23	0.22	0.21
23	0.1	0.23	0.23	0.23	0.22	0.21	0.21
24	0.1	0.23	0.23	0.23	0.22	0.22	0.21
25	0.1	0.23	0.23	0.22	0.22	0.22	0.21
26	0.1	0.22	0.23	0.23	0.22	0.22	0.21
27	0.1	0.22	0.23	0.23	0.22	0.21	0.21
28	0.1	0.23	0.23	0.23	0.22	0.21	0.21
29	0.1	0.23	0.23	0.23	0.22	0.21	0.21
30	0.1	0.23	0.23	0.23	0.22	0.21	0.21

4.2 CFD Simulation Result

4.2.1 CFD Validation

Comparing the two results, it can be seen that the simulation results agreed with the experimental results for all locations because the percentage differences are less than 25%. Figure 4 below shows a graph of the percentage difference between measurement and simulation results for all locations. The percentage difference for formaldehyde concentration still does not exceed the 25% maximum acceptance percentage difference by the ASHRAE Standard. The result simulation of formaldehyde concentrations at locations A, C and D exceeded the result measurement, while locations B and E did not exceed.

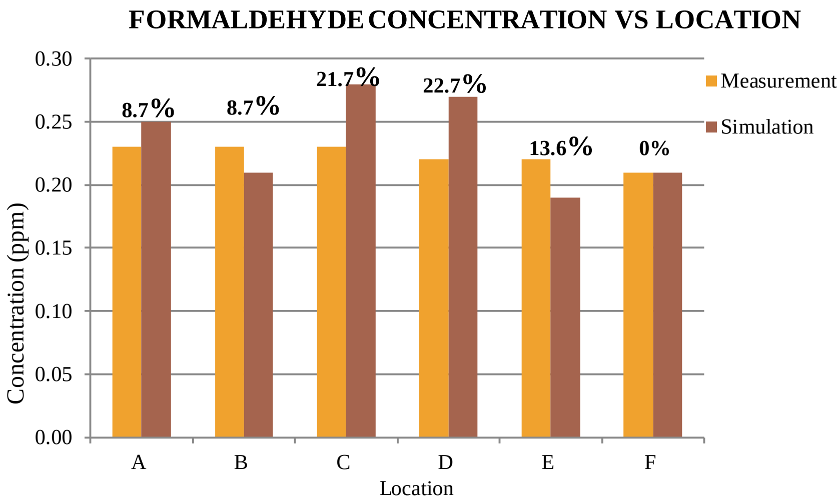
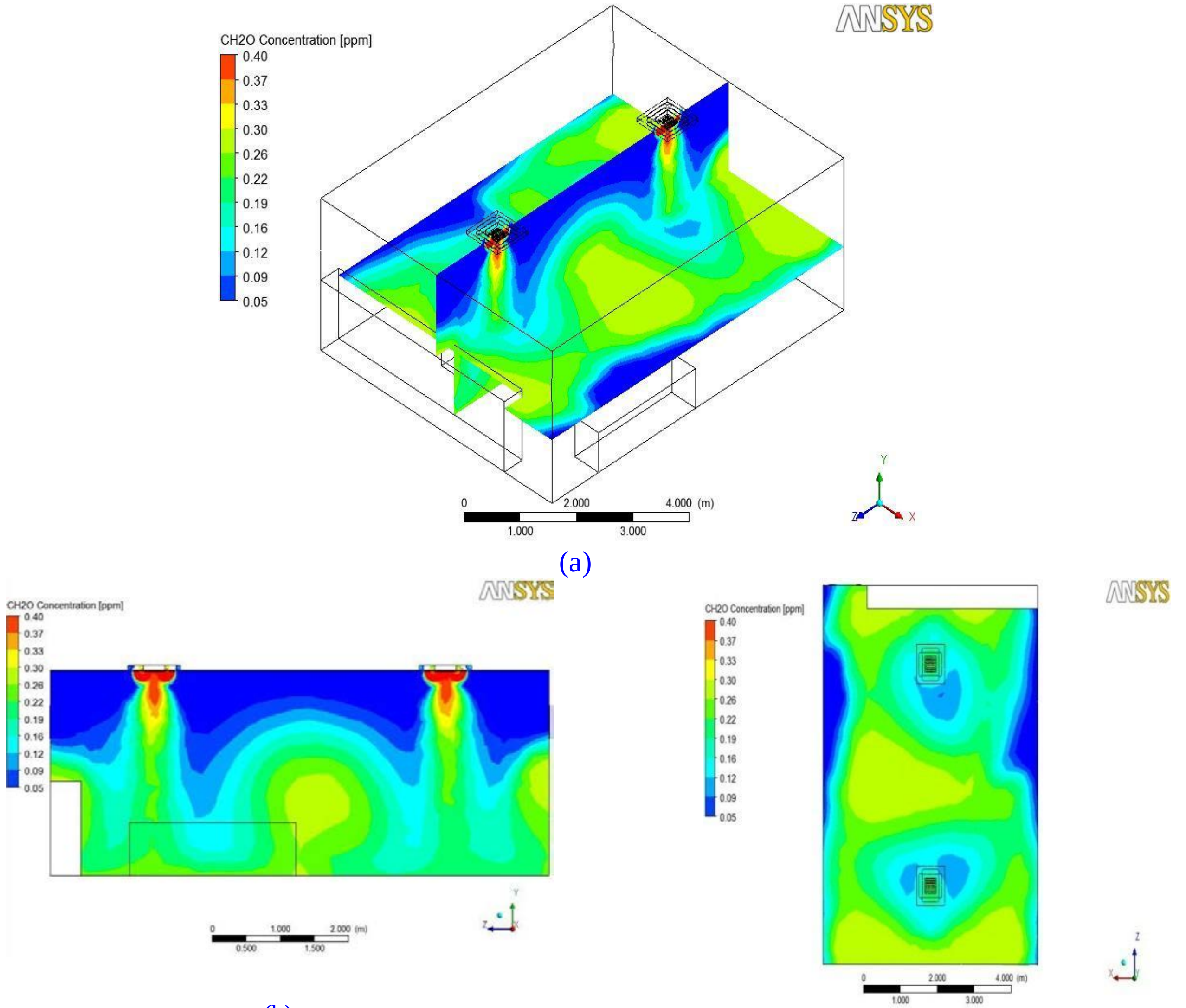


Figure 4: Graph of the percentage difference between measurement and simulation result.

From the chart, it can be seen that by far the concentration is higher at the center of the room which is at locations C and D than in any other locations, most probably because the concentration is accumulated from both inlets of a diffuser.

4.2.2 Formaldehyde Distribution

The formaldehyde distribution is observed at the vertical plane y-z (x = 2.9 m) and horizontal plane x-z (y = 1.2 m). Figure 5 shows the predicted formaldehyde distribution on horizontal and vertical planes inside the Dean's office. The most important relevant finding is that in a steady-state condition, the center between ceiling cassette air condition has a higher concentration zone compared to other zones. The concentrations are accumulating at the center due to the effect of recirculation flow. The concentrations at the inlet to the outlet are higher due to the source and airflow configuration.



(a)

(b)

(c)

Figure 5: The formaldehyde distribution on horizontal and vertical planes for close door a) 3D view b) 2D from front view c) 2D from a top view (created by authors)

4.3 Parametric Study

The new boundary condition on the door is influenced by the result of formaldehyde concentration and distribution. The simulation analyses the effect of formaldehyde concentration when the main door is open. There are two doors inside the room but only one door (the main door) is always open during working time as the other door is for emergency escape.

4.3.1 Formaldehyde Concentration

The data on formaldehyde concentrations for all locations are used to compare with the formaldehyde concentration of the actual environment (closed door). Figure 6 presents the results of formaldehyde concentration obtained along the line intersecting the horizontal and vertical plane for the open main door of all locations. The graph reveals that the highest concentration is at location C which is 0.20 ppm while the lowest concentration is at location D which is 0.09 ppm.

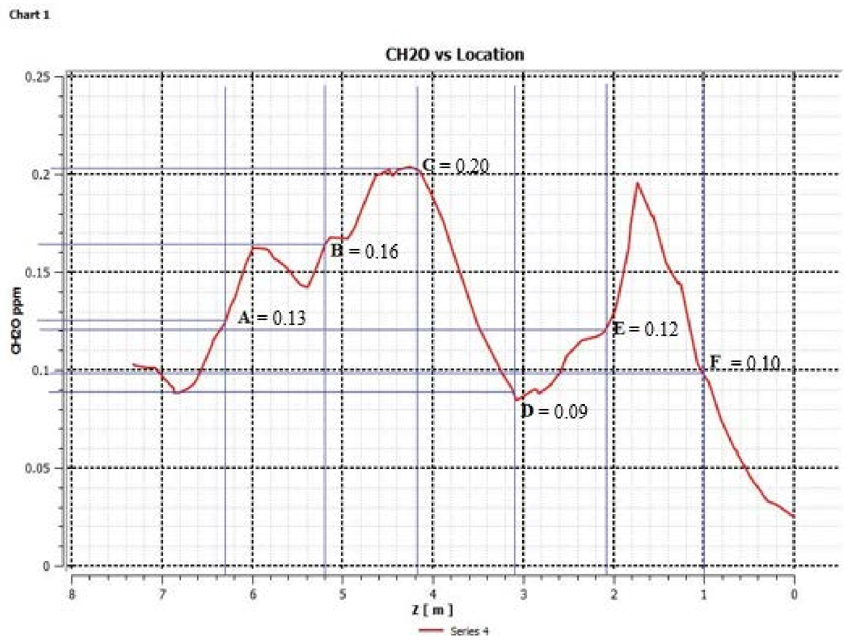


Figure 6: The graph of formaldehyde concentration along the line intersects the horizontal and vertical plane for the open main door (created by authors)

The formaldehyde concentration of open door condition is compared with the actual environment (closed door). Table 5 shows the formaldehyde concentration of closed doors and open doors for all locations.

Table 5: Formaldehyde concentration of closed door and open door for locations A-F.

Location	Formaldehyde Concentration (ppm)	
	Close Door	Open Main Door
A	0.25	0.13
B	0.21	0.16
C	0.28	0.20
D	0.27	0.09
E	0.19	0.12
F	0.21	0.10

From the table above, we can see that the formaldehyde concentration of the open main door has lower concentration than the actual environment (closed door). The open-door condition reported a considerably more healthy environment than the closed-door condition because an open door can reduce the level of formaldehyde concentration. From this data, we can see that formaldehyde concentration resulted in the highest value at location C which is below ceiling cassette air conditioning and near the source of the formaldehyde contaminant. The open door can be immediately implemented by the Dean to reduce the level of formaldehyde concentration.

4.3.2 Formaldehyde Distribution

Figure 7 shows the formaldehyde distribution of horizontal and vertical planes for the open main door. Data from the top view result (X-Z plane) (Figure 7) can be compared with the data in Figure 5. It shows that the higher concentration is in the range of 0.20 ppm compared to the closed door which has a higher concentration in the range of 0.30 ppm. The results, as shown in Figure 7, indicate that the contaminant is diluted through the door which can reduce the formaldehyde concentration in the Dean's office.

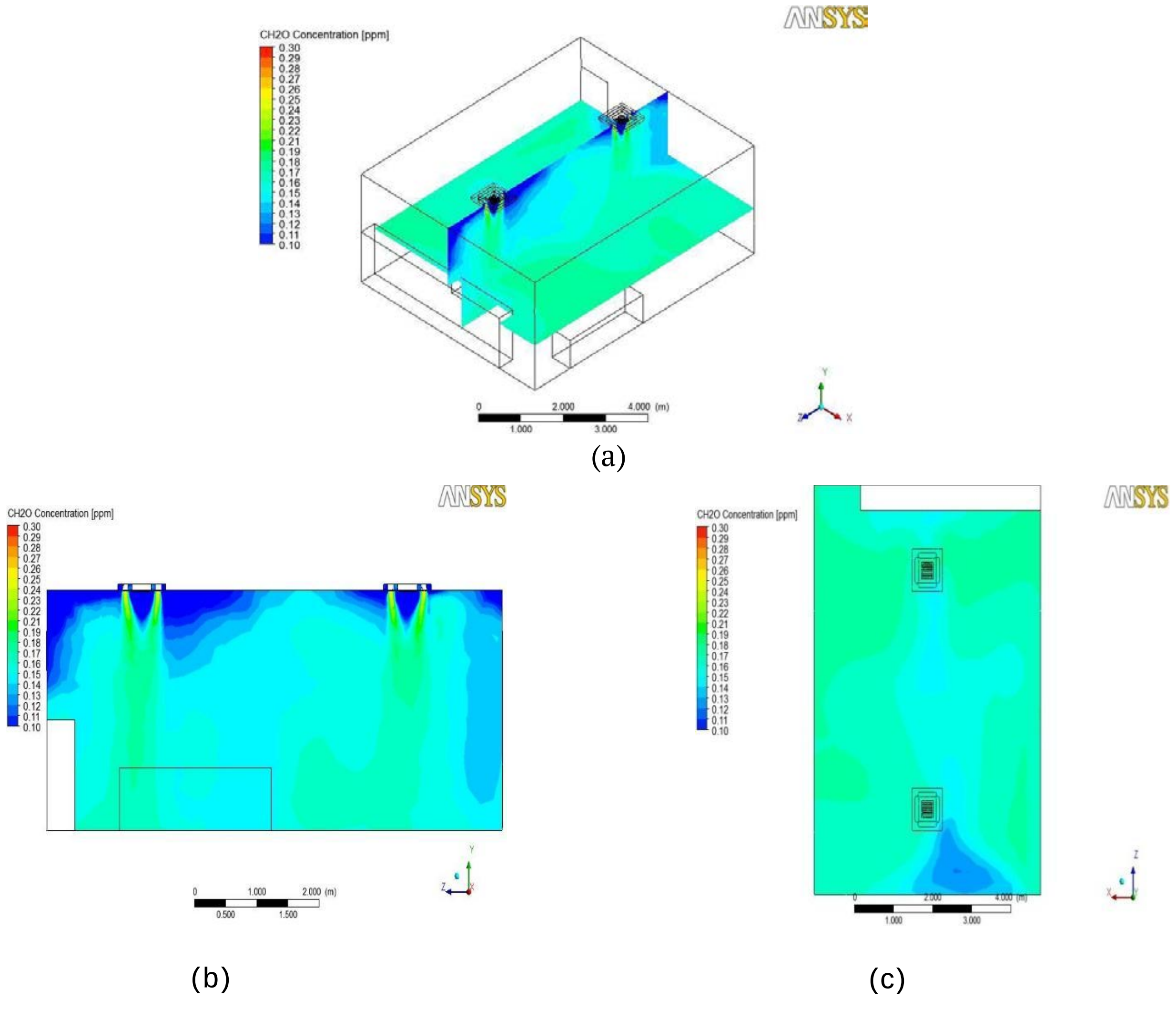


Figure 7: The formaldehyde distribution on horizontal and vertical planes for the open door a) 3D view b) 2D from front view c) 2D from a top view (created by authors).

To keep indoor comfortable conditions and low air pollutants concentrations, ventilation and air conditioning systems have gradually evolved into general design specifications. High concentrations of air pollutants would reduce the resistance of the natural immune system and make the human body more vulnerable to viral diseases (Domingo et al., 2020).

5 Conclusion

Returning to the objectives posed at the beginning of this study, it is now possible to state that the formaldehyde concentration inside the Dean's office exceeds the maximum limit by OSHA standards. In this investigation, the aim is to suggest an effective way to reduce the level of formaldehyde concentration. The purpose of this study is to investigate whether the formaldehyde concentration and distribution inside the Dean's office are healthy or not. The quantified formaldehyde concentration in the Dean's office through field measurement has been shown to exceed the maximum limit of 0.1 ppm. After predicting formaldehyde distribution through CFD simulation, the center between ceiling cassette air conditioners has a higher concentration zone compared to other zones. It is shown that the recirculation ventilation system influences formaldehyde distribution. However, it has a significant effect on formaldehyde concentration in the Dean's office. To reduce the level of formaldehyde concentration in the Dean's office, a parametric study was performed. It is shown that the open main door can reduce the level of formaldehyde concentration.

6 Availability of Data and Material

Data can be made available by contacting the corresponding author.

7 Acknowledgement

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