CFD Simulation Analysis of Thermal Comfort in a Small Office

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Abstract: This study presents a 3D model of a small office to analyze and evaluate thermal comfort in Vietnam. Predicted Mean Vote index (PMV) is used to evaluate thermal comfort satisfaction. Using the CFD simulation, PMV is calculated based on the effects of temperature field, air flow, wind speed, and radiation. And, two different airflow rates of 0.4 m^3s^{-1} and 0.56 m^3s^{-1} were considered. The results show that, at the airflow of 0.4 m^3s^{-1}, 70% of users around the areas supply air vents are satisfied, while only most of the people in the return air vent area are not satisfied with the thermal comfort. When the airflow is 0.56 m^3/s, the percentage of people satisfied with thermal comfort in areas near the supply air vent increased by 95%, and the thermal comfort in the return air vent area was also improved.

Keywords: CFD; HVAC; Office; OpenFoam; Thermal Comfort

1. Introduction

The heating, ventilation and air conditioning (HVAC) systems supply a comfortable environment for people working in buildings. However, the HVAC systems often account for 40% of a building's energy consumption[1]. Therefore, research of green buildings[2–5] and environmentally friendly cooling systems[6–10] as well as the thermal comfort conditions[11–16] for living[17–21] and working space[22–27] are receiving a lot attention.

Solano et al.[28] conducted a survey of HVAC electricity consumption, indoor temperature, relative humidity, global horizontal radiation, and outdoor temperature to analyze thermal comfort. The results showed that the number of people, who were satisfied with the temperature, is more than 80% when the HVAC system operated with minimal energy consumption. A study by Ono et al.[29] showed that 10% energy savings were achieved by building an optimal comfort model to control the HVAC system.

The numerical method[30,31] is also widely applied in this field from last decade. The important of heat pack distribution is reviewed by Zhang et al.[32]. And the role of numerical methods is proved in order to demonstrate the distribution in detail. Coupled with exergy method and CFD simulation, Xu et al.[33] show the improvement the efficiency and thermal comfort of occupants. Recently, Wang et al[34], demonstrated the CFD based deep learning model to assess the indoor thermal comfort. This study proposed a prediction method based on the Convolutional Neural Networks-Long Short-Term Memory model and using CFD simulation as a data-set generator. The results show a high accuracy and rapid response.

In addition, CFD simulation approach is also used to analyze the thermal comfort in outdoor environment[16,35]. Chen et al.[31] conducted the experiment and CFD simulation of thermal comfort of outdoor environment. And in hot weather, the efficacy of elevated walkways is confirmed, which improves the pedestrian thermal comfort.

In this study, thermal comfort in a typical small office, with working conditions and climate conditions in Hanoi, is evaluated using the OpenFoam. The purpose of this is to contribute to the provision of a preliminary assessment method for thermal comfort in buildings. Based on the CFD simulation results, new design is proposed to improve the thermal comfort of the building and optimize energy consumption for the HVAC system of this office.

2. Numerical Methodology

2.1. The thermal comfort assessment standard

Thermal comfort is evaluated as a comfortable level two index, including the Predicted Mean Vote (PMV) and the

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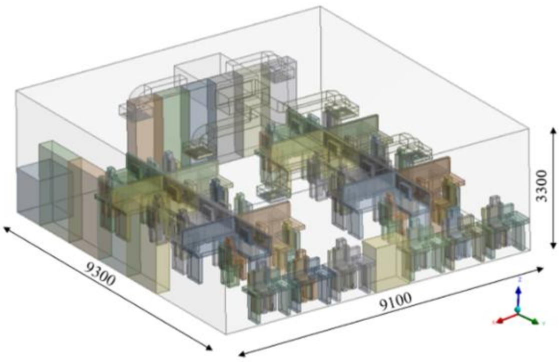
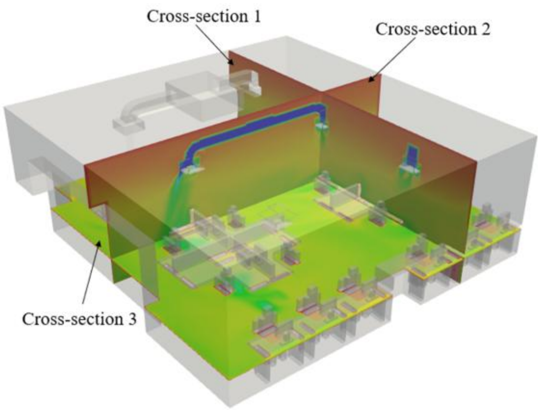
a) Top view



b) Isoview



c) Cross sections

Fig. 1: The 3D model of the office

Predicted Percentage Dissatisfied (PPD)[36]. PMV is a measure of the average vote of a large group of people based on the heat balance of the human body through six variables, as described in Equation (1), including air velocity (v_{air}), air temperature (T_{air}), mean radiant temperature (t_r), relative humidity (RH), metabolic rate

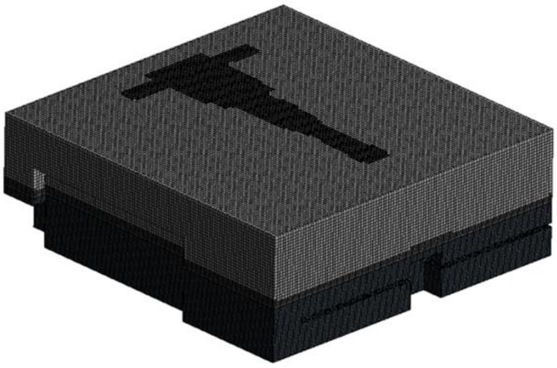


Fig. 2: The sample of grid generation

(Met) and clothing (Clo) as following:

$$PMV = f(T_{air}, v_{air}, RH, t_r, Clo, Met) \quad (1)$$

The PPD index indicates a quantitative prediction of the percentage of thermally dissatisfied people, who feel too warm or too cool. The PPD is defined by equation (2) as follows:

$$PPD = 100 - 95 \times e^{(-0.03353 \times PMV^4 - 0.2179 \times PMV^2)} \quad (2)$$

As suggested by ASHRAE Standard 55[37], the acceptable range of PMV for a comfortable indoor conditioned environment is from -0.5 to +0.5.

2.2. The numerical Model

In the current study, the simulation is carried out using OpenFoam solver. The fluid is incompressible flows. The Reynolds-Averaged Navier-Stokes turbulent model k-RNG was applied. The equations of mass, momentum, and energy conservation are as follows:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho u) = 0 \quad (3)$$

$$\frac{\partial \rho u}{\partial t} + \nabla.(\rho u u) + +\nabla.\left(\mu_{eff} \nabla u\right) + \nabla.\left(\mu_{eff} \nabla u^T - \mu_{eff} \frac{2}{3} tr \nabla u^T I\right) = -(\nabla \rho).g.h.f - \nabla p_{rgh} \quad (4)$$

$$\frac{\partial (\rho h)}{\partial t} + \nabla.(\rho u h_e) + \nabla.\left(\rho u (0.5\sqrt{U} + \frac{p}{\rho})\right) - \nabla.\alpha_{eff} \nabla T = S_{radiation} + S_h \quad (5)$$

Based on CAD drawing, the 3D model of the office was drawn as shown in Figure 1.

The model was meshed, and mesh quality and independence were evaluated prior to simulation. The total number of elements is 2784199. The sample of grid is shown in Figure 2

The simulation conditions used in this study are based on actual design parameters, where the temperature of air supply is 16°C, the initial temperature in the room is 30°C, and the room relative humidity 65%. In the simulation, the

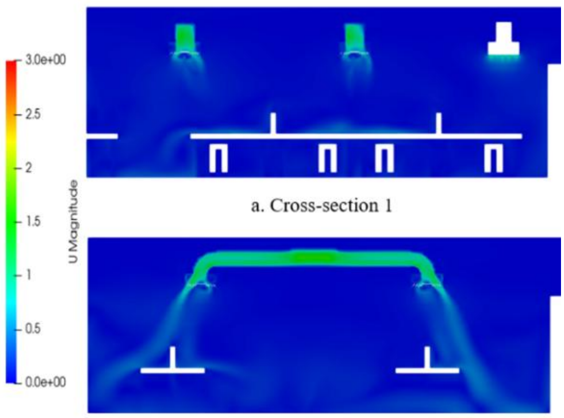
Fan coil unit (FCU) supplies airflow rates of 0.40 and 0.56 m^3/s, corresponding to the high and medium room-supply settings, respectively. The thermal resistance parameters of clothing I_{cl} is 0.5 m^2 °C and metabolic rate M is 1.2 Met for people working in an office environment.

3. Results and Discussions

The distribution of airflow in current office is depicted in Figure 3. The airflow distribution from the FCU to the air supply box through the vent is uneven in both directions. Specifically, the airflow is distributed away from the air box towards the two sides of the branch air duct and the flow in the remaining directions is right below the air box. The velocity in the air duct and air box ranged from 1 to 1.5 ms-1. After leaving the air box, the velocity decreases to 0.5-1 ms-1, and velocity in return air is about 1-1.5m/s. Figure 4 shows temperature distribution in the office. The air supply temperature after leaving the air vent is about 16oC, and the temperature of the airflow going away from the vent to the room space is about 20oC to 23oC. Most office spaces have a temperature of 26oC. The temperature at the ceiling of the room is hotter due to the ventilation effect. The temperature around the staff at the return air vent tends to be higher, about 27-28oC. This is due to the maldistribution of flow at the air vent, which leads to the maldistribution of temperature. As the consequence, it causes discomfort for people. In contrast, the low temperature is low in the central area of the room, which is around 23oC. It shows that the interior prevents air from moving in the room, making the wind distribution between areas unevenly.

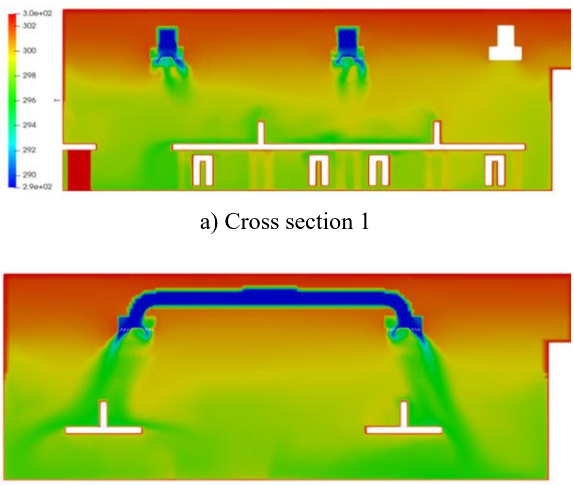
Figure 5 shows a comparison of temperature distribution at two different airflows. The results show that the higher airflow results in the better temperature distribution, which is around 25-26oC. The temperatures of some areas around the working person are still higher than average temperature in the room, especially the area near the return vent.

Thermal comfort and the percentage of dissatisfied people are shown in Figure 6 and Figure 7. The thermal comfort with the supply airflow of 0.4 m3s-1 is demonstrated in Figure 6(a) and Figure 7(a). The PMV is in the range of 0.5 to 1 for most of the space in the room, corresponding to only about 25% of people dissatisfied with thermal



a. Cross-section 1

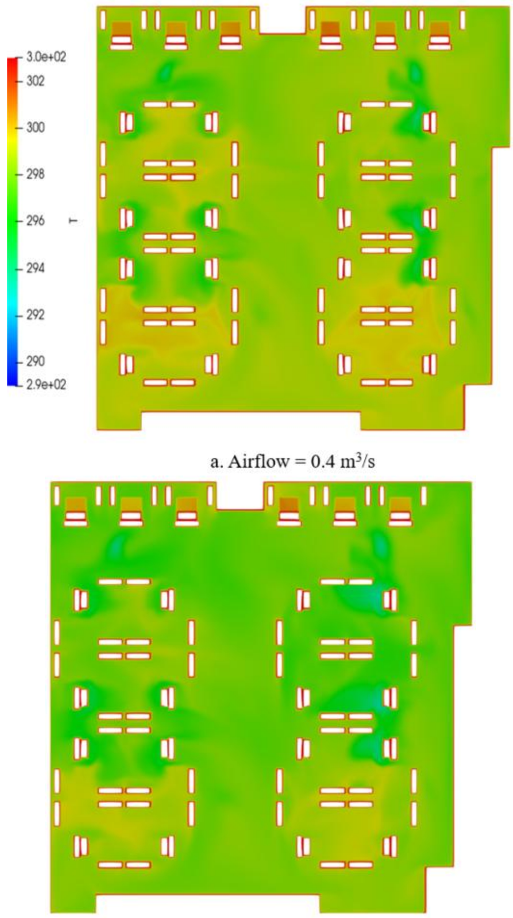
Fig. 3: The distribution of airflow velocity (m/s) in the office



a) Cross section 1

b) Cross section 2

Fig. 4: The temperature distribution (K) in the office



a. Airflow = 0.4 m^3/s

b. Airflow = 0.56 m^3/s

Fig. 5: The distribution of temperature (K) in the office

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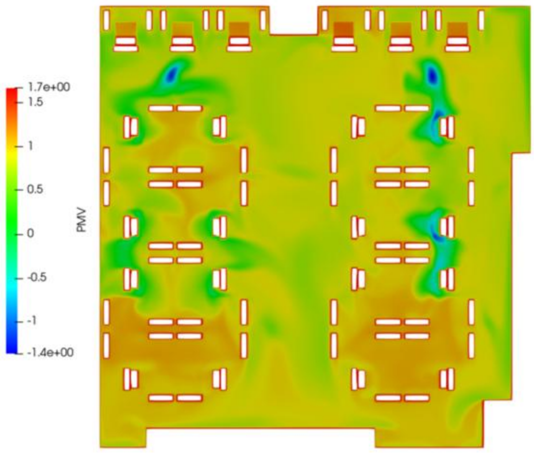
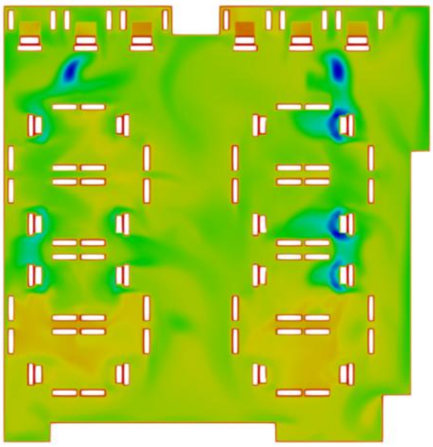


a. Airflow = 0.4 m^3/s



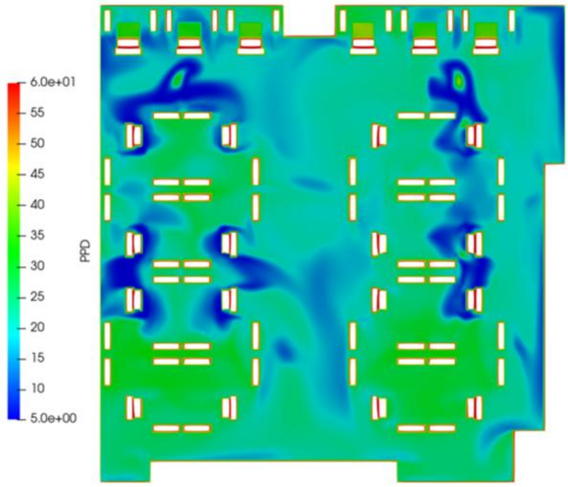
b. Airflow = 0.56 m^3/s

Fig. 6: The distribution of PMV with different airflow

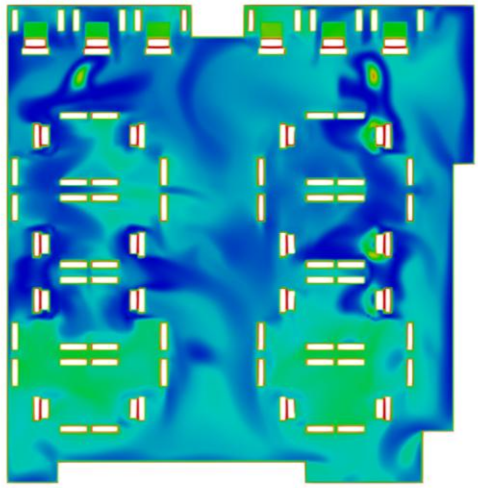
comfort. For the area near the air supply vent, a small area with PMV in the recommended range of -0.5 to 0.5 is observed. A few points with PMV in the range of -1 will give a cold feeling and correspond to 30% of people being dissatisfied. In contrast, the area at the return air vent shows the highest PMV, which is in the range of 1.2 to 1.5. In this area a hot feeling appears and corresponds to about 35% of people dissatisfied with thermal comfort.

In Figure 6(b) and Figure 7(b), the thermal comfort is evaluated when the airflow is 0.56 m3s-1. The results show that the PMV is better than the case with airflow of 0.4 m3s-1. The thermal comfort area is larger, with a range of -0.5 to 0.5, corresponding to the percentage of people satisfied with thermal comfort is about 80%. A few points near the supply air with PMV less than -1 around seating place give a cold feeling, corresponding to 30-50% of people dissatisfied with this temperature. The area near the return air vent still shows the highest PMV, about 0.8 to 1.2. This is the area that gives a hot feeling in the room and corresponds with approximately 30% of people dissatisfied with thermal comfort.

To evaluate the local PMV and PPD, a probe matrix is set



a. Airflow = 0.4 m^3/s



b. Airflow = 0.56 m^3/s

Fig. 7: The distribution of PPD (%) with different airflow

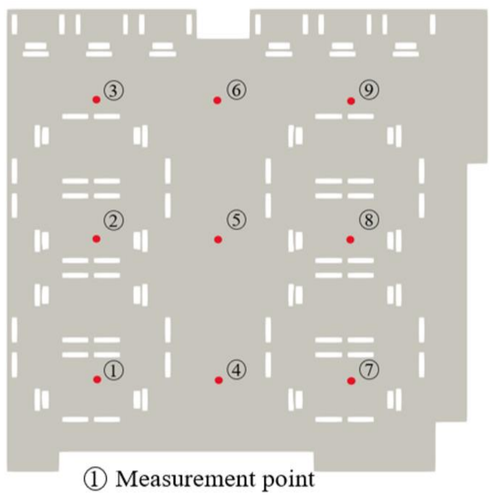


Fig. 8: The probe matrix

up in the simulation as illustrated in Figure 8. A cross section is 1 meter above the ground that is closed to the

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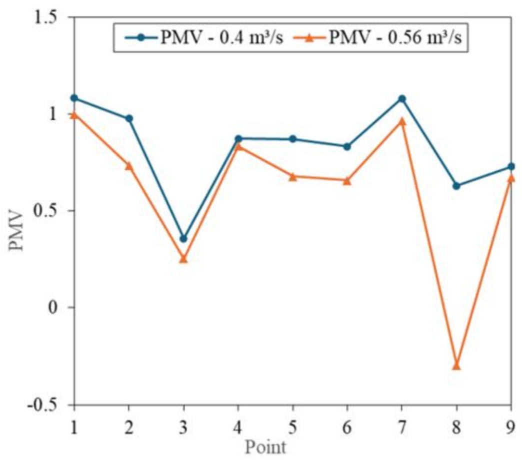
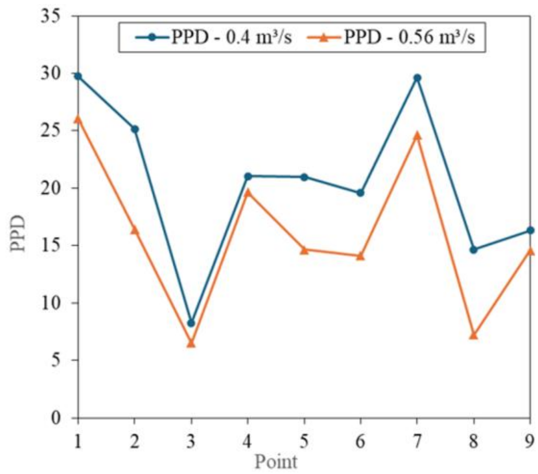


a) PMV



b) PPD (%)

Fig. 9: The probe of PMV and PPD with different airflow inside office

mid point of person sitting at work.

Figure 9a and show the thermal comfort assessment in the current room with flows of 0.4 m3s-1 and 0.56 m3s-1, respectively. In general, the thermal comfort distribution in the room in the two air supply cases is maldistribution. When the airflow is higher, the thermal comfort is better. In both cases, the return air vent area (points 1 and 7) has the worst comfort conditions, corresponding to 30% of people being dissatisfied with the temperature. Points 3 and 8 near the comfort air vent area are within the recommended range, corresponding to only 5% of people being dissatisfied with the recommended thermal comfort. The remaining points are within acceptable ranges for thermal comfort.

4. Conclusions

In the present paper, the distribution of thermal field temperature, airflow, and thermal comfort in a small office was evaluated by the CFD simulation method. In this study, two different airflows of 0.4 m3/s and 0.56 m3/s were used. The simulation results showed that the airflow distribution at the supply air boxes was not uniform throughout the space; there were areas with large velocity distribution and areas with very small incoming velocity. Therefore, the temperature distribution in the office space was not uniform with a large temperature difference. Thermal comfort in the working space at higher airflow for PMV was in the range of -0.5 to 0.5, within the recommended range. Meanwhile, at lower airflow, PMV was in the range of 0.5 to 1.2 for a warm feeling. In addition, the results of the study also showed the potential application of CFD simulation tools in the pre-evaluation of HVAC system design.

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