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Numerical Investigation of Thermal Comfort in an Aircraft Passenger Cabin

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ABSTRACT

This study presents the results of a pilot numerical study of the thermal comfort in the aircraft passenger cabin. The computations have been performed using the Computational Fluid Dynamics (CFD) technique. The overall thermal comfort at temperatures of 15 °C – 20 °C was discussed based on the PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) indexes. Results indicate that the air velocity and its direction toward the passengers have a considerable impact on their thermal comfort. However, a small variation in temperature has a limited effect on thermal sensation and thus do not jeopardize the overall thermal comfort.

KEYWORDS

Aircraft Passenger Cabin, Thermal Comfort, Numerical Simulation, PMV (Predicted Mean Vote), PPD (Predicted Percentage of Dissatisfied)

1 INTRODUCTION

The passenger aircraft cabin is a narrow and enclosed space usually with a high population density. Due to the long flight duration nowadays, thermal comfort becomes an essential factor to consider in the design stage. Aircraft manufacturers, such as Boeing and Airbus, have given considerable effort to the thermal comfort improvement (Pang et al. 2014).
There are several methods applied to study thermal comfort in such areas. In some research studies, the well-known predicted mean vote (PMV) model (Fanger 1970) was used, however, some others conducted field thermal comfort surveys. It is also possible to adopt numerical simulations and computational fluid dynamics (CFD) to predict the local skin temperature and calculate the thermal comfort.
Cui et al. (2014) conducted a field measurement in an aircraft cabin, to map the influential parameters such as air temperature, relative humidity, black globe temperature, and air velocity. A questionnaire survey among the passengers was also performed.
They concluded that passengers were not thermally satisfied as they experienced warm feelings. The thermal comfort map exhibited non-uniformity; middle cabin always had a higher temperature. However, the vertical temperature gradient, as well as air velocity, were reported to be within the comfort zone.
In another study, the local and overall thermal comfort of aircraft cabin passengers were investigated (Park et al. 2011). It has been concluded that overall thermal sensation in the simulated aircraft cabin was relatively well, however, the local thermal discomfort was reported to be high. Haghighat et al. (1999) were performed measurements during 43 commercial flights with a duration longer than one hour in which temperature, relative humidity and carbon dioxide concentration were continuously monitored. Results showed that the mean air temperature was

not well controlled during most of the flights and it fell to the cooler side of the comfort zone for summer conditions. The achieved data showed that average air temperatures were between 21 and 24°C and only 2 out of 15 flights satisfied the thermal comfort requirement for summer conditions.
The present research study aimed at investigating the thermal comfort situation in a commercial aircraft cabin using computational fluid dynamics (CFD) simulation. PMV and Predicted Percentage Dissatisfied (PPD) were also numerically calculated.

2 METHOD

The aircraft cabin model used is shown in Fig. 1-a. The overall dimension of the cabin is 3.6 m×2.3 m×2.7 m (H) and eight passengers are sitting in the section of the cabin and each passenger is a heat source of 60 W. The air introduced to the cabin from the ceiling diffusers and exhausted out from the floor openings. Three different airflow rate of 5 l/s, 10 l/s and 15 l/s each with two air temperature of 15°C and 20°C were considered.

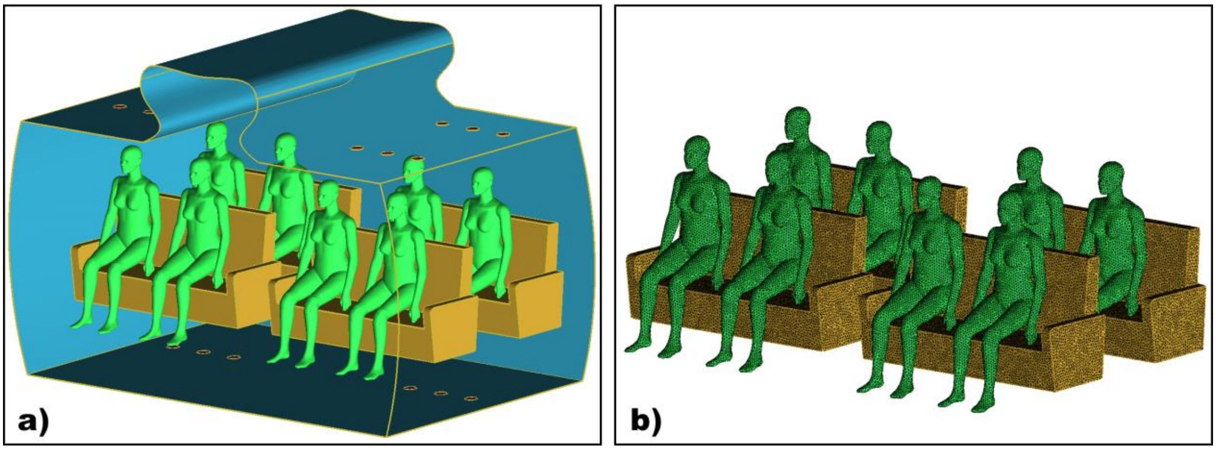

Figure 1: Airplane cabin geometry and its corresponding grid generated with ICEM CFD

The commercially available CFD program, ANSYS FLUENT 18.0, with a RANS based turbulence model of the renormalization group (RNG) k–ε model (Yakhot et al. 1992) was adapted to conduct the simulations. The cabin space was subdivided into 2.9 million tetrahedral grids using ICEM CFD (Figure 1-b). Grid dependency test was carried out to make sure that grid resolution has no effect on the outcome. All cabin walls were considered to be adiabatic to the outdoor environment. The discrete ordinates (DO) radiation model was used to determine the radiative heat flux contribution.
In order to map the thermal comfort in indoor environments, several influential parameters need to be predicted, including air velocity, temperature, humidity, and turbulence intensity. Here, the PMV/PPD method developed by Fanger (1970) was implemented. PMV is a parameter for thermal comfort evaluation based on the humidity, air temperature and velocity, metabolic rate, and clothing isolation. In the current study, a user-defined function developed to calculate the PMV from the CFD simulation results. The empirical equation to PMV index is as follows:

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$$PMV = [0.303exp(-0.036M) + 0.028]\times \left\{ \begin{array}{c} (M-W) - 3.05\times 10^{(-8)} f_{cl}[(T_c l + 273.15)^4 - (T_r + 273.15)^4] \\ - f_{cl} h_{conv}(T_{cl} - T_a) - 3.05[5.733 - 0.007(M-W) - 0.001 p_w] \\ -0.42[(M-W) - 58.15] - 0.0173M(5.867 - 0.001 p_w) - 0.0014M(34 - T_a) \end{array} \right\} \quad \textbf{(1)}$$

The PPD index can be calculated as the following:

$$PPD = 100 - 0.95exp(-0.03353PMV^4 - 0.2179PMV^2) \quad \textbf{(2)}$$

A detailed explanation of the above equation is given in ISO 7730-2005 (*ISO 7730:2005*, 2005). A seven-point thermal sensation scale of PMV was furnished in Table-1. The acceptable thermal environment for general comfort is recommended to be in the range of (– 0.5 < PMV < 0.5).

Table 1: Seven-point thermal sensation scale

+3	*Hot*
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
	Cool
-2	Cool
-3	Cold

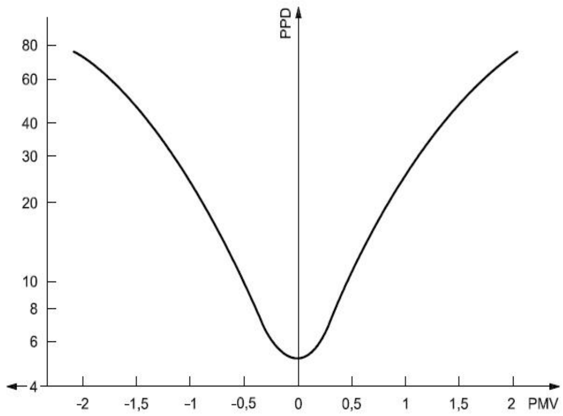

Figure 2: PPD as a function of PMV

The PMV index is valid for steady-state conditions, however, can be still valid during minor fluctuations of one or more of the variables. The PMV can be applied to measure the level of comfort criteria. It is also can be used to establish requirements for different levels of acceptability.

3 RESULT AND DISCUSSION

Figure 3 depicts the airflow field at the vertical plane within the cabin. The velocity distributions show the strong downward airflow patterns toward the head of passengers. This might result in discomfort especially in higher velocities in case of 15 l/s.

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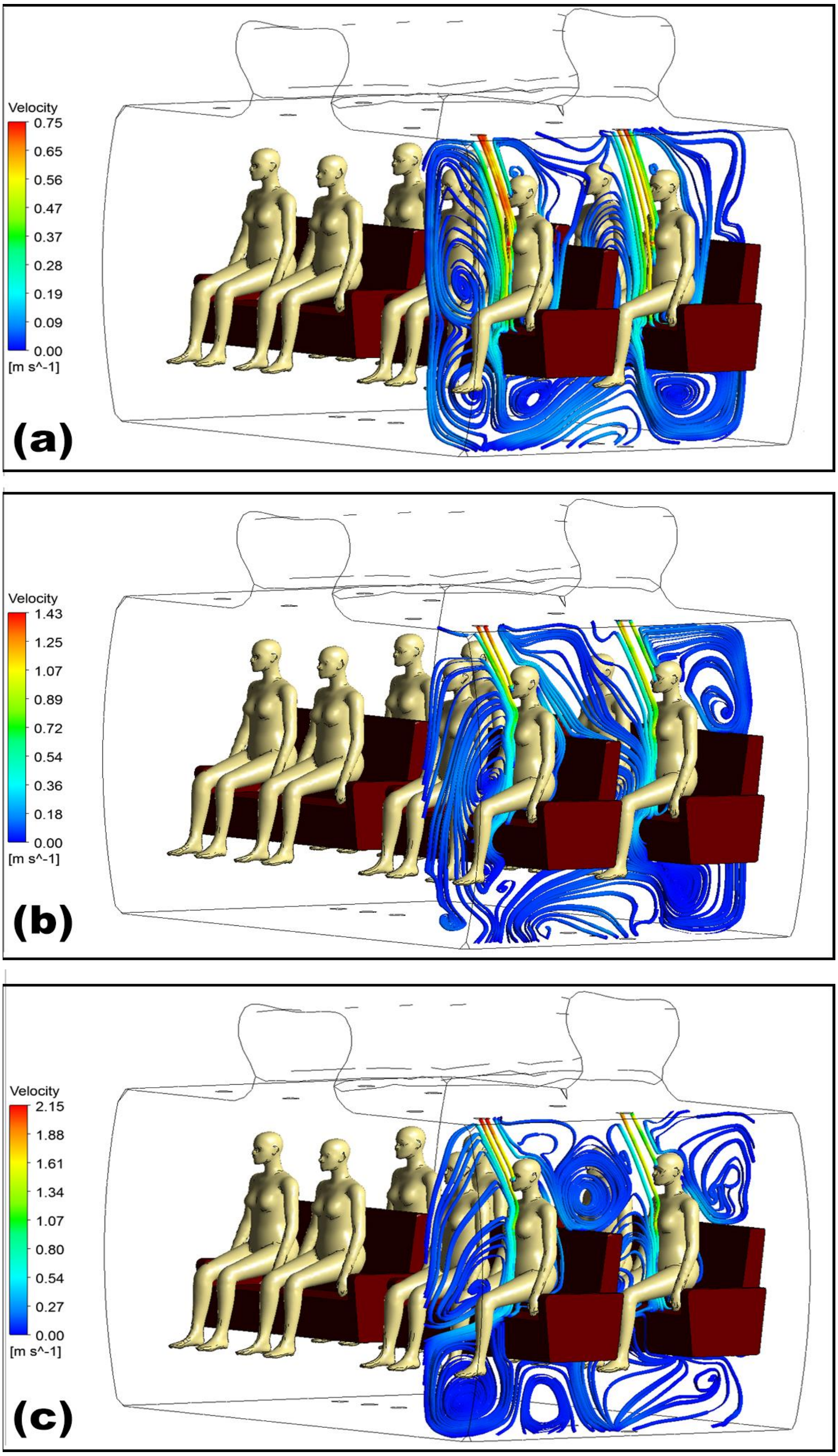

Figure 3: Airflow pattern at a vertical plane in the aircraft cabin with different airflow rate:
a) 15 l/s   b) 10 l/s   c) 5 l/s

Figure 4 and figure 5 show the PMV and PPD indices for the airflow and temperature combinations were simulated.

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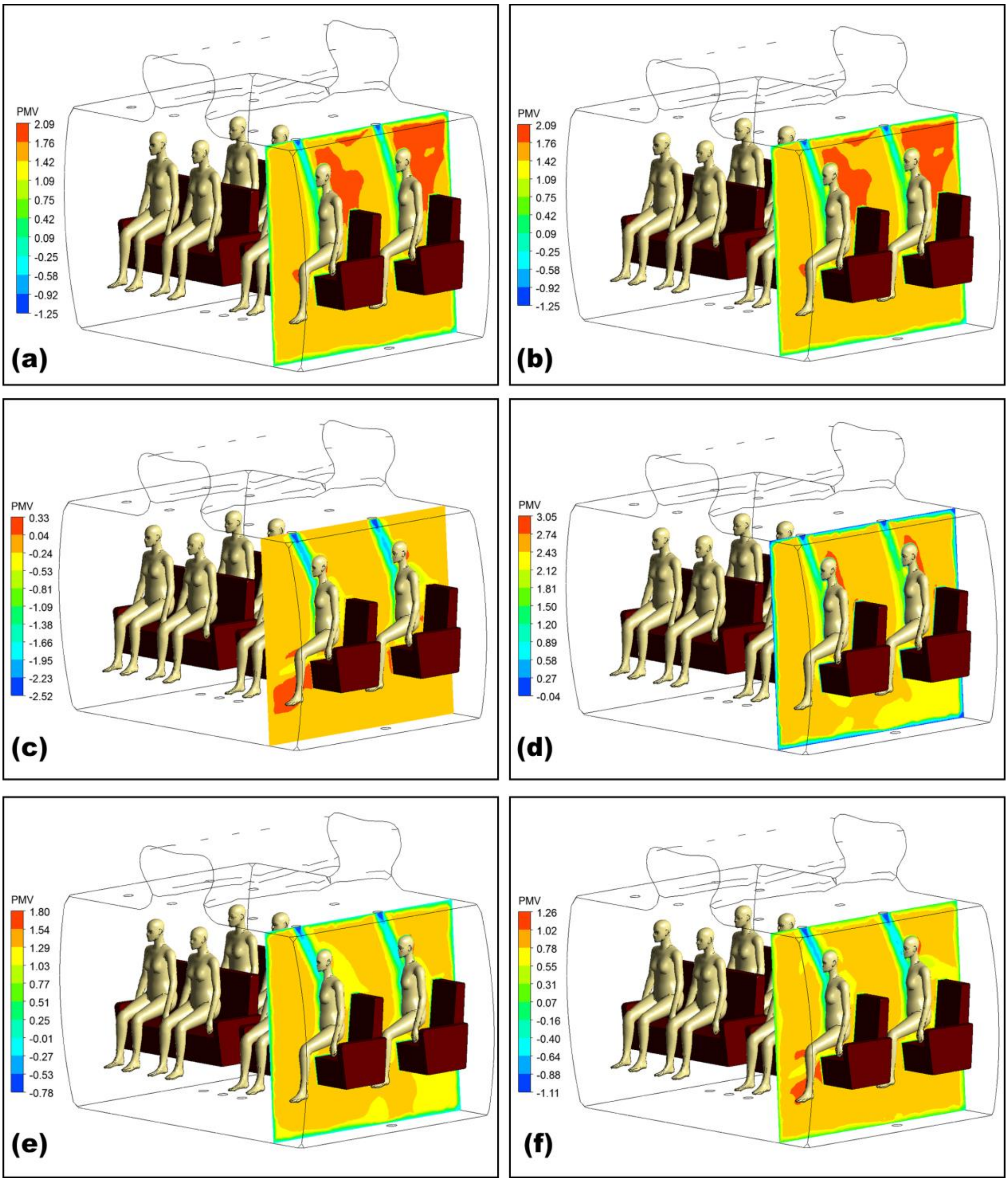

Figure 4: PMV contour plot with different inlet air temperature and velocity:

a) 5 l/s and 15 °C	b) 10 l/s and 15 °C	c) 15 l/s and 15 °C
d) 5 l/s and 20 °C	e) 10 l/s and 20 °C	f) 15 l/s and 20 °C

Comparing the PMV results for three inlet velocity and two inlet air temperature indicated that slightly more thermally satisfactory results could be achieved when the cabin was ventilated by higher temperature. On the other hand, a lower degree of satisfaction achieved when the incoming air had a lower temperature and higher velocity. The highest dissatisfaction can be observed, in almost all case studies, in the head and neck area of passengers resulted from higher air velocity in this area.

PPD index depicted in figure 5 shows almost the same correlation.

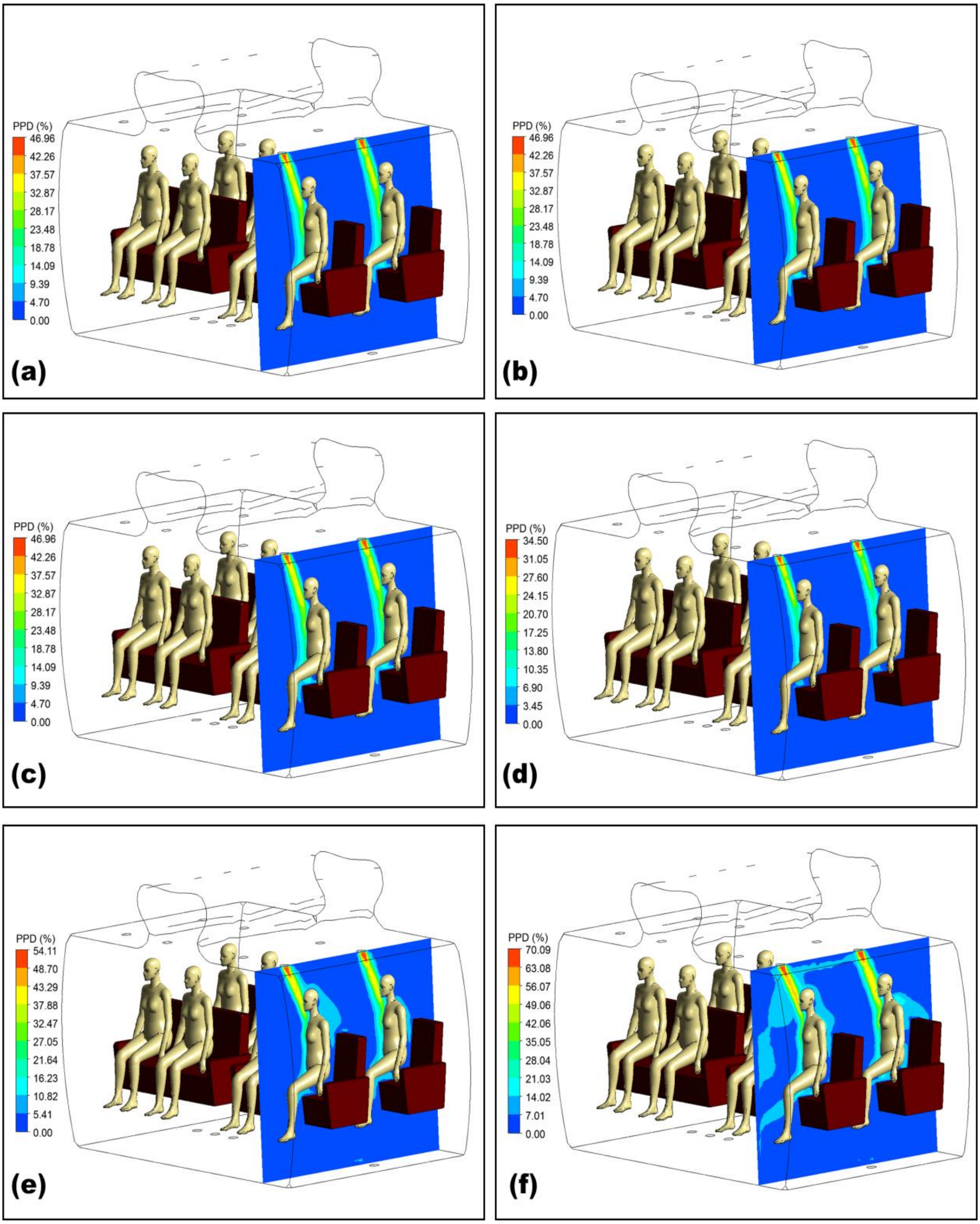

Figure 5: PPD contour plot on the same vertical plane as figure 4, with different inlet air temperature and velocity:

a) 5 l/s and 15 °C b) 10 l/s and 15 °C c) 15 l/s and 15 °C
d) 5 l/s and 20 °C e) 10 l/s and 20 °C f) 15 l/s and 20 °C

Figure 6 shows the thermal comfort of passengers in the all simulated inlet boundary conditions. In only one case out of all six, PMV/PPD indices fall within the comfort zone. The highest degree of thermal satisfaction achieved when the cabin was ventilated at volume airflow rate of 15 l/s and temperature of 15°C.

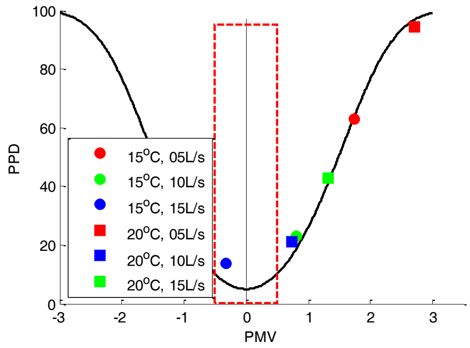

Figure 6: PMV and PPD for all case studies

The worst-case scenario, however, was when the inlet air volume flow rate was assigned to 5 l/s with a temperature of 20°C.

4 CONCLUSIONS

Using CFD tool to simulate the thermal comfort level in commercial aircraft cabin could provide a good complement to the measurements.

This study presents a CFD analysis of thermal comfort in an aircraft cabin. The PMV and PPD were calculated under different inlet air temperature and velocity to evaluate thermal comfort of the passengers. It was found that more thermal satisfaction might be achieved when the cabin ventilated at an airflow rate of 15 l/s and temperature of 15°C. However, the lowest thermally satisfaction was predicted when the cabin was supplied with a lower airflow rate of 5 l/s and higher temperature of 20°C.

In a normal practice, thermal comfort estimated by considering the mean air velocity and temperature, as well as mean relative humidity over the entire cabin space. Nonetheless, the mean of above-mentioned quantities may vary substantially throughout the domain and thus give a deviated estimation.

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