Bio-Effluents Tracing in Ventilated Aircraft Cabins

Petrone G.*, Cammarata L., Cammarata G.
Department of Industrial and Mechanical Engineering, University of Catania
*Corresponding author: Viale A. Doria, 6 – 95126 Catania, Italy – gpetrone@diim.unict.it

Abstract: Ventilation and indoor air quality (IAQ) are issues of very high interest, determining comfortable conditions for occupants and no-contaminated local atmosphere. The aircraft cabins are more confined and have a higher occupant density than other indoor environments such as offices or residential houses. The passengers and the crew share a closed and ventilated cabin, which brings potential risk of infection and inhalation of airborne pollutants. The present study deals with a numerical investigation on bio-effluents transport and diffusion in ventilated aircraft cabins. Several layouts for ventilation system (Mixing Air Distribution, Under Floor Displacement, Personalized Air Distribution) are analyzed in order to strike a balance between air quality degradation and comfort conditions for passengers. Analyses are based on bio-effluent concentrations monitoring inside the cabin.

Keywords: IAQ, transport phenomena, HVAC systems.

1. Introduction

The bio-effluents diffusion in indoor environments is a very actual issue of interest because of the potential risk of infections transmission between people sharing the same atmosphere. This issue takes top relevance when considering indoor environment characterized by very high occupant density. One of the most representative of these environments is an aircraft cabin. In order to avoid high concentration regions of any air pollutant inside the cabin, environmental control system is devoted to dilute the contaminant concentration by introducing fresh air inside the cabin. The air distribution system is a very important component of the environmental control system since it is used to distribute conditioned air properly to the cabin, providing a healthy and comfortable cabin environment. Since an aircraft cabin has a, more complex geometry and a lower outside air supply rate per person as compared to buildings, it is very challenging to design a comfortable and healthy cabin environment for commercial airplanes. Currently, mixing air distribution (labeled as MAD in this paper) systems are used to distribute air in an aircraft cabin.

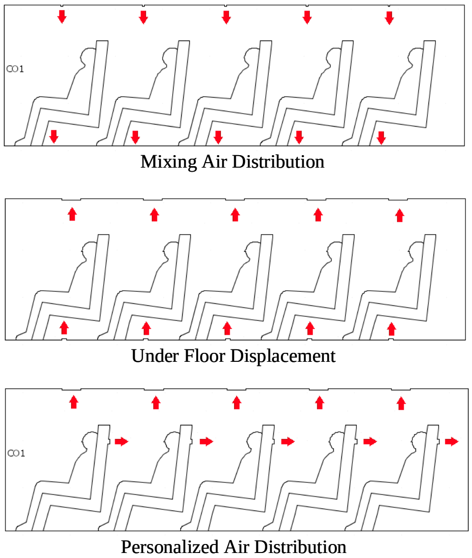

Figure 1. Layout of ventilating systems considered in this study.

Conditioned air is supplied at the ceiling level with a high velocity and then mixes with the air in the cabin. The air temperature in the cabin is rather uniform and contaminants in the cabin are diluted. However, the mixing air distribution system could easily spread bio-effluents from one infected passenger to other passengers because of the high velocity inlet air jets. On the other hand, displacement air distribution systems have been used for buildings with considerable success. In an under-floor displacement air distribution system (labeled as UFD in this paper), clean air is supplied to an indoor space from the floor. Then contaminated air is exhausted from the ceiling level. Furthermore, a new system with personalized air supply has begun to emerge. A personalized air distribution system (labeled as PAD in this paper) supplies clean and cool air directly to the breathing area of a person. The system can create a preferred microenvironment with clean air. The personalized air distribution system can provide a superb air quality, but it could cause a draft perception on the occupant's face. Although both UFD and PAD ventilating systems have been successfully applied in buildings, they come just from experimental application for aircraft cabins and MAD system only is usually applied. This study deals with a numerical investigation in order to analyze the performance of the described different layouts of ventilating systems in assuring the best air quality conditions.

2. Modeling

Numerical models are built up in COMSOL Multiphysics v.3.5a. The geometry of the considered system consists in a 2D representation of 5 rows of seats standing inside an aircraft cabin. Depending on the considered air distribution system (MAD, UFD, PAD), small differences can be remarked in model geometries: as an instance, the geometrical elements used as inlet and outlet sections for fluid flowing the control volume. Geometrical elements are designed too in order to represent seated human occupants inside the cabin. Transient Navier-Stokes equations for the system, assuming Newtonian and uncompressible fluid, read as in following:

$$\rho\frac{\partial u}{\partial t}+\rho u\cdot\nabla u=\nabla\cdot\left[-pI+\eta\left(\nabla u+\left(\nabla u\right)\right)^{T}\right]$$

$$\nabla\cdot u=0$$

Physical properties of fluid are considered constant; they are computed at atmospheric pressure (101325 Pa) and supposed ambient temperature (20 °C). The momentum equations are coupled with a transport-diffusion equation, based on the concentration of the carbon dioxide breathed out by the cabin occupants:

$$\frac{\partial CO_2}{\partial t}+\nabla\cdot\left(-D_{CO_2}\nabla CO_2\right)=-u\cdot\nabla CO_2$$

Previous equations are solved with the following boundary conditions:

<u>Momentum equations</u>

- Adherence conditions at solid walls;
- Imposed constant velocity for fresh air inlets;
- Symmetry conditions at vertical control volume confinements;
- Atmospheric pressure at recovery grids for air;
- Periodic inlet velocity function at bio-effluent inlet (nose of occupants).

<u>Transport-diffusion equation</u>

- Impermeable conditions at solid walls;
- Convective flux at recovery grids for air;
- Periodic concentration flux function at bio-effluent inlet (nose of occupants).

The periodic functions used as boundary conditions simulate the human breathing of occupants during time and the relative mass rate of carbon dioxide introduced in the cabin. Referring to the inlet velocity function, it is evaluated considering: the mass rate of air inhaled by a standard person every breathe, the air density, the surface of the nose holes and the breathing frequency. The carbon dioxide mass rate incoming in the control volume is as well computed following the same analytic procedure. In this case the concentration flux is evaluated considering the CO_2 molecular mass and the rate of CO_2 contained in air breathed out. As an instance, the CO_2 concentration flux function applied to one of the occupants nose surface is reported in Figure 2.

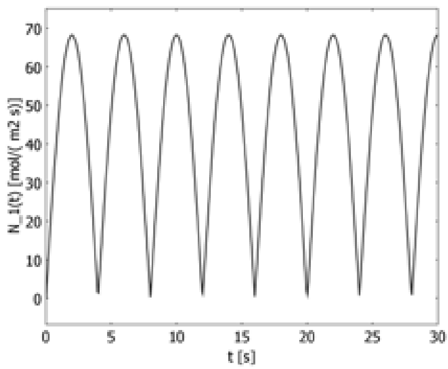

Figure 2. Time function of the CO_2 flux.

In order to simulate more real conditions it is supposed that passengers breathe not in phase each other. The phase displacement is imposed in 0.2 second for each passenger. Once geometries meshed (one of the adopted computational grid is reported in Figure 3), the numerical solutions are carried-out for each model.

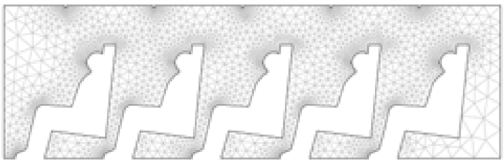

Figure 3. Computational grids for MAD system.

The time integration lies on a BDF free time step scheme. Linear system are at each time step solved by a direct method. The time range used for computations is 120 seconds. Referring to some preliminary test runs, this time range largely assures a particle introduced at time 0 to join the outlet section of the computational domain for any air distribution system studied.

3. Results

The obtained results are presented in this section. Figure 4 globally shows the velocity field at t=120 [s] for the MAD, UFD and PAD air distribution systems.

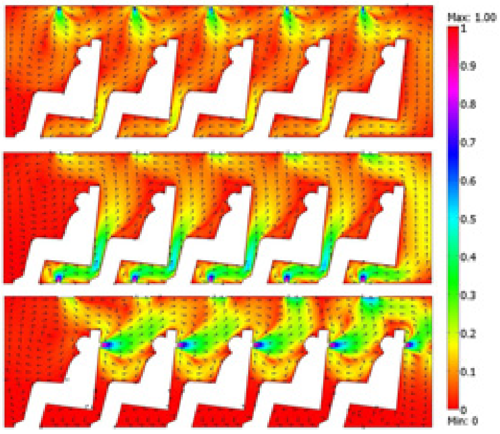

Figure 4. Velocity field [m/s]: MAD, UFD and PAD system.

It is to notice as the detected motion field in proximity of the first and the last row of seats is slightly different from others. This is the effect of the control volume confinement. Anyway, it can be assumed that results referring to the intermediate rows are representative of the physical problem. An enlargement of the velocity distribution close to the third row of seats is presented in Figure 5-7 for the MAD, UFD and PAD system respectively.

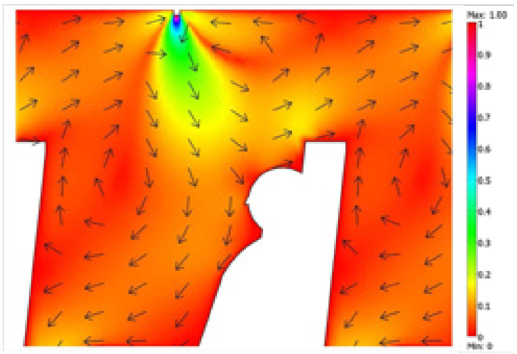

Figure 5. Velocity field [m/s]: enlargement close to the 3rd row of seats for MAD system.

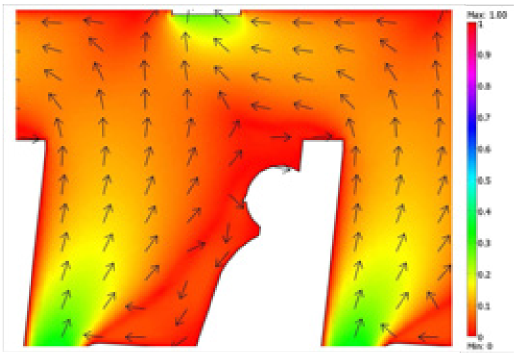

Figure 6. Velocity field [m/s]: enlargement close to the 3rd row of seats for UFD system.

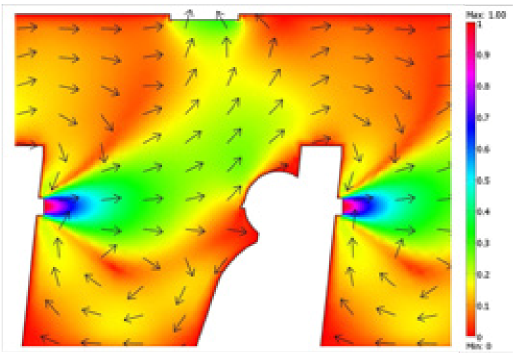

Figure 7. Velocity field [m/s]: enlargement close to the 3rd row of seats for PAD system.

The significant differences in air dynamics can be appreciated from a distribution system to another. It is to remark the relative difference in the air velocity magnitude occurring close to the passenger faces. While the MAD and UFD systems assure magnitude of velocity lower than 0.15 m/s, the PAD system application determinates values comprised between 0.3-0.4 m/s. This represents the threshold value of induced discomfort in passengers due to a potential air draft perception. Otherwise, Figure 8 reports concentration levels of carbon dioxide detected at t=120 [s].

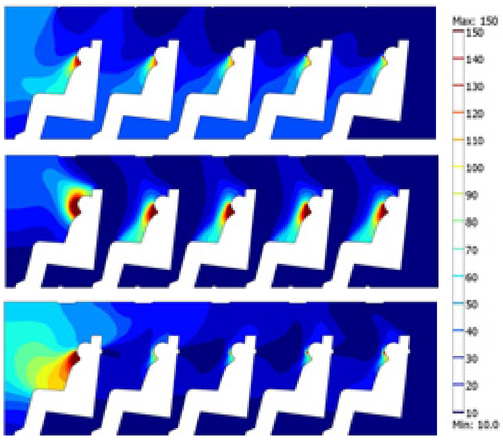

Figure 8. CO_2 concentration levels [mol/m^3]: MAD, UFD and PAD system.

It can be observed as, from the air quality point of view, the best air distribution system appears the PAD one. In fact, it assures a good dilution of the bio-effluent breathed out by the passengers, determining very low concentration of it close to the occupant's nose. On the other hand, the UFD system is characterized by almost stagnant condition in that region, so that high levels of CO_2 are detected. The MAD system determinates intermediate conditions from the previous ones. These remarks are confirmed by Figures 9-11 where enlargements of Figure 8 are plotted for each air distribution system and at different time steps. As previously introduced, it is assumed a breathing frequency of 0.25 Hz, so that images reported in Figures 9-11, captured in the range of time (60; [1]; 63 [s]), describe the concentration of bio-effluent along a complete breathing act close to the passenger's face.

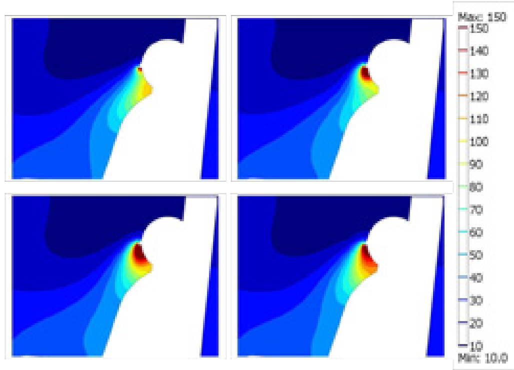

Figure 9. CO_2 concentration levels [mol/m^3] at t=(60; [1]; 63 [s]): enlargement close to the 3rd row of seats for MAD system.

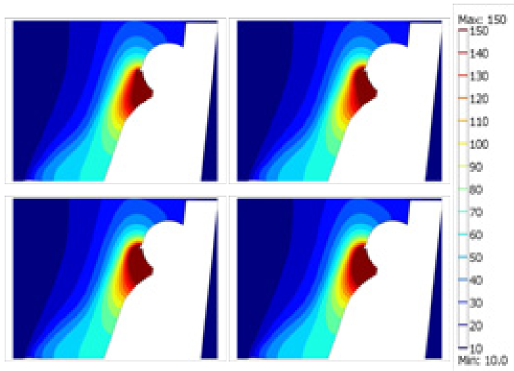

Figure 10. CO_2 concentration levels [mol/m^3] at t=(60; [1]; 63 [s]): enlargement close to the 3rd row of seats for UFD system.

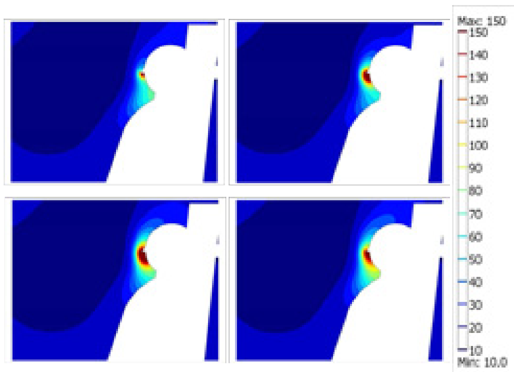

Figure 11. CO_2 concentration levels [mol/m^3] at t=(60; [1]; 63 [s]): enlargement close to the 3rd row of seats for PAD system.

Figures 9-11 well elucidate the effect of the periodic function applied for breathing simulation also. Focalizing now the attention on the potential contamination risk inside the cabin, Figures 12-14 show the tracing obtained by monitoring the path of a particle introduced, at the initial time of simulation, close to the nose of the passenger seated in the third row.

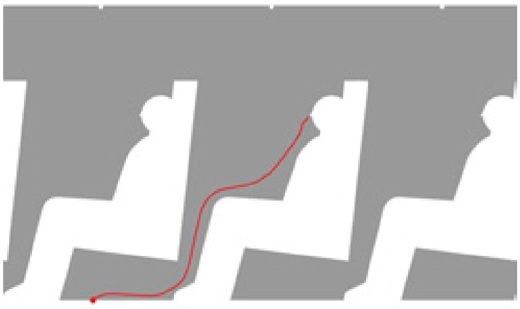

Figure 12. Particle tracing for MAD system. Final time of processing t=23[s].

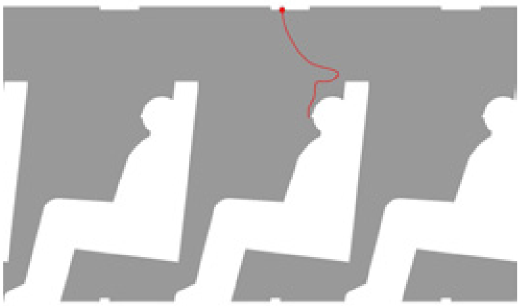

Figure 13. Particle tracing for UFD system. Final time of processing t=24[s].

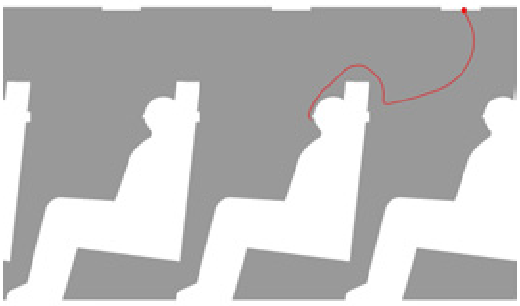

Figure 14. Particle tracing for PAD system. Final time of processing t=10[s].

This kind of post-processing allows to well understand the transport effect on a small mass generated by the fluid flow. Some remarks need to be pointed out. For each air distribution system, the particle path follows the streamlines of air flow. In MAD system, fresh air coming from the cabin ceiling blows the particle down as far as the recovery grids arranged on the floor. The time needed is 23 about seconds. In UFD system, fresh air coming from the bottom push up the particle as far as the grids, this time located on the roof. The time needed is about 24 seconds. In the PAD system, fresh air blown by the seat in front of the breathing passenger let his bio-effluent flow toward the passenger lodged in the rear row. The particle is then blown toward the outlet section by the rear air jet. The time needed is about 10 seconds.

4. Conclusions

Numerical simulations are carried-out in order to strike a balance between air quality degradation and comfort conditions for passengers standing in an aircraft cabin potentially equipped by three kinds of air distribution system. Results mainly show as from the comfort condition the most appropriate system is the UFD system. In fact it assure the lower velocity level close to the passenger's face. From the air quality point of view, the PAD system represent instead the best choice because it allows very low level of stagnant bio-effluent close to the passenger's nose. Anyway, referring to the contamination risk inside the cabin, this system is detected to be the most critical because it allows particle breathed out by a passenger to be potentially inhaled by another. Globally it appears that in absence of relevant challenges to be pursued in the most recent UFD and PAD systems, the classical MAD represent the better compromise between opposite requirements.

5. References

1. Aijun Wang, Yuanhui Zhang, Yigang Sun, Xinlei WangAuthor, Experimental study of ventilation effectiveness and air velocity distribution in an aircraft cabin mockup, *Building and Environment*, **43**, 337-343 (2008)

2. Tengfei Zhang, Qingyan (Yan) Chen, Novel air distribution systems for commercial aircraft cabins, *Building and Environment*, **42**, 1675-1684 (2007)

3. Qingyan Chen and Zhao Zhang, Prediction of particle transport in enclosed environment, *China particuology*, **3**, 364-372 (2005)

4. M.B. Hocking, Passenger aircraft cabin air quality: trends, e ects, societal costs, proposals, *Chemospere*, **41**, 603-615 (2000)

5. M. Kavgic, D. Mumovic, Z. Stevanovic, A. Young, Analysis of thermal comfort and indoor air quality in a mechanically ventilated theatre, *Energy and Buildings*, **40**, 1334-1343 (2008)

6. Zhang Lin, T.T. Chow, C.F. Tsang, K.F. Fong, L.S. Chan, CFD study on effect of the air supply location on the performance of the displacement ventilation system, *Building and Environment*, **40**, 1051-1067 (2005)

7. Zhang Lin, T.T. Chow, K.F. Fong, Qiuwang Wang, Ying Li, Comparison of performances of displacement and mixing ventilations. Part I: thermal comfort, *International Journal of Refrigeration*, **28**, 276-287 (2005)