25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

PERFORMANCE EVALUATION OF MIXING AND DISPLACEMENT VENTILATION SYSTEMS ON THE DISPERSION AND REMOVAL OF EXPIRATORY DROPLETS IN AN AIRCRAFT CABIN: AN EXPERIMENTAL ANALYSIS

Douglas Fabichak Junior
Program of Post-Graduation of Mechanical Engineering, Polytechnic School, University of São Paulo, São Paulo, Brazil
fabichak@usp.br

Victor Barbosa Felix
INSPER - Institute of Education and Research
Program of Post-Graduation of Mechanical Engineering, Polytechnic School, University of São Paulo, São Paulo, Brazil
victorbf@insper.edu.br

Arlindo Tribess
Department of Mechanical Engineering, Polytechnic School, University of São Paulo, São Paulo, Brazil.
atribess@usp.br

Abstract. *This article presents results of dispersion and removal of expiratory droplets for two ventilation systems in an aircraft mock-up cabin: the conventional aircraft Mixing Ventilation system (MV) and the Displacement Ventilation system (DV) usually used in buildings. The performance tests were performed inside a mock-up of a regional aircraft cabin with 12 seats, 3 rows with 4 abreast. Passengers were simulated using heated manikins. The tests were performed considering air supply temperature conditions at 18 °C and particle generation at two points at the end of the cabin: near the fuselage and near the aisle. Particles simulating a person sneezing were generated and measured at the breathing zone, 1.10 m from the floor. The results showed that the proposal DV system can be used successfully in aircraft cabins regarding dispersion and effectiveness in removal expiratory droplets. The DV system compared to the conventional system MV reduced the dispersion of particles along the cabin and increased the removal of particles up to 31.4% for particles of 2 to 3 μm, and up to 32.0% for particles of 3 to 5 μm. Finally, it is important to emphasize the greater efficiency of the DV system in removal small particles compared with the MV system. It is particularly important since smaller particles are easily inhaled and can cause serious health problems.*

Keywords: *Ventilation systems, Air Quality, Expiratory droplets, Experimental analysis, Aircraft cabins.*

1. INTRODUCTION

In commercial aircraft cabins, high occupancy density and small airflow spaces result in relatively low per-person ventilation rates. This kind of an unique environment can also generate areas of stagnation and reduction in the rate of dilution of potentially pathogenic contaminants exhaled by humans. In addition, the limited internal space with a large number of occupants makes the passengers very close to each other (Fiser and Miroslav, 2013, Volavý et al., 2013, Li et al., 2014, You et al., 2016).

A major concern regarding the health of aircraft occupants, especially after SARS outbreaks, swine flu (H1N1), bird flu, etc., is directly related to cross-contamination among passengers (Olsen et al., 2003, Mangili et al., 2005), which has motivated governments, companies and research institutions to invest heavily in research and development.

The global outbreak of SARS virus (Severe Acute Respiratory Syndrome) in 2003 showed that the spread of airborne contaminants can still be an uncontrollable event, since it was quickly spread around the world, mainly because it infected people traveling by plane to distant cities (Olsen et al., 2003). As a result, studies of contamination in aircraft cabins have been focusing on air pollution resulting from the dispersion of expiratory pollutants generated by people (Wan et al., 2005, Zhang et al., 2009, Wan et al., 2009, Sze To et al., 2009, Yan et al., 2009, Gupta et al., 2011, Conceição, 2012, Bosbach et al., 2012, Chen et al., 2012, Pang et al., 2013).

The ventilation system commonly used in aircraft cabins is the supply air from the top, through the ceiling, and exhaustion to the bottom, with mixing of the air in the cabin, Mixing Ventilation – MV. The result is a nearly uniform temperature in the cabin and a wide dispersion of contaminants.

Although the MV system typically provides an environment with low temperature stratification, problems of thermal comfort have been verified. Furthermore, its characteristic of air mixture can more easily spread infectious diseases along the cabin, (Gao et al., 2007 and Zhang et al., 2009).

To try to solve the problems of thermal comfort and air quality, new ventilation and air distribution aircrafts systems are beginning to be studied and tested, such as the Displacement Ventilation system, DV, already applied in buildings, (Zhang and Chen, 2007).

Besides, with the increase in the autonomy of flight of new aircrafts and the increase in the number of passengers in air travel, there is also concern about the stay for longer periods in this type of environment. Studies related to air quality have also been developed in such a way as to be a differential in the competitiveness that exists between the few aeronautical industries.

It is a field of activity in which the advances made are not normally disclosed in the open literature. So it is precisely in this context that this article is inserted, that of testing the ventilation system that is commonly used in aircraft cabins, the MV system, and a new proposal system, the DV system.

2. METHODS

2.1 Cabin Geometry

The analysis of the dispersion of expiratory droplets was performed inside a mock-up simulating a regional aircraft cabin with 12 seats, 3 rows with 4 abreast. Passengers were simulated using heated manikins. The experiments were performed considering mixing ventilation (MV) and displacement ventilation (DV) under air supply temperatures 18 ±0.5 °C.

For the MV system, Figure 1, was considered the usual procedure adopted in the aerospace industry. Ie, with 40% of the airflow supplied by diffusers installed at the top of the bins and 60% of the airflow supplied by diffusers in part by lower side of the bins, with 100% of the exhaust air flow by grilles installed at the bottom side of the cabin. Similarly, the DV system, Figure 2, was considered 100% of the supply airflow by bottom side diffusers, with 40% of the exhaust air flow by grids localized on the top of the bins and 60% of the exhaust airflow through grilles located at the bottom side of the bins.

Following ASHRAE 161 (2007), in each experiment the supply airflow rate of 34 m³/h (20 cfm) per person was used, making a total air supply in the mock-up of 12 people of 408 m³/h (240cfm). The supply airflow rate was measured and monitored by the measurement of air velocity in the exhaust ducts using Pitot tubes. The experiments were performed with full new outside air and with filtering control of the particles greater than 2 µm in the outside air.

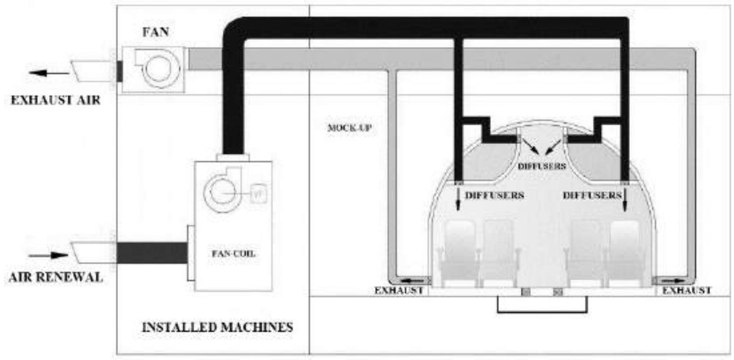


Figure 1. Air distribution system - Mixing Ventilation (MV)

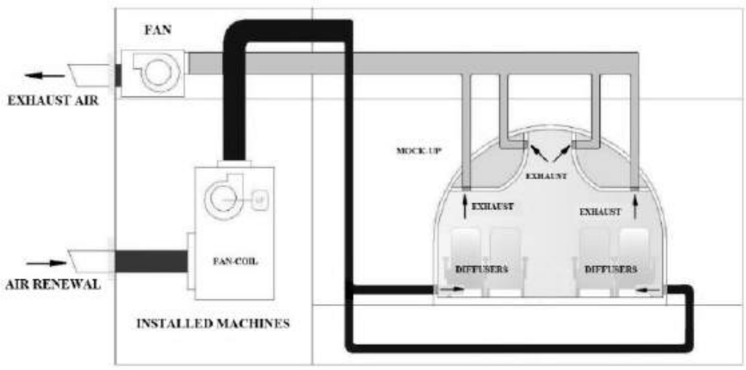


Figure 2. Air distribution system – Displacement Ventilation (DV)

2.2 Experimenal procedure

In this study three omnidirectional probes with temperature sensors were simultaneously used to carry out the air velocity and temperature measurements and for the analysis of the air flow pattern. The probes with the temperature sensors were installed at the heights of 0.10 m, 0.60 m and 1.60 m in a mobile stand, tripod type. Each probe recorded a total of 300 points at the respective height of measurement. The measurements were conducted in three longitudinal planes, three rows 1, 2 and 3, and at five transverse points, columns A, B, C, D and E, at three different heights 0.10 m, 0.60 m and 1.10 m, simulating people sitting (Figure 3), with a total of 45 measurement positions.

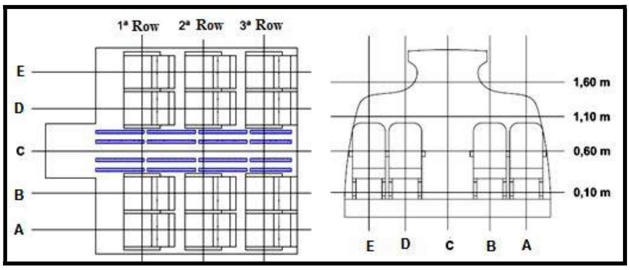
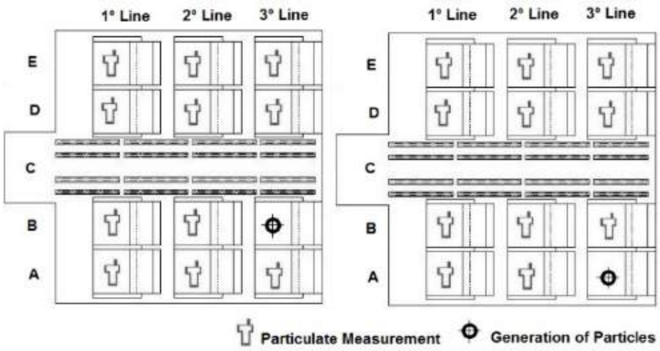


Figure 3. Plans of measurement of air velocities and temperatures along the cabin

In the present study it was simulated continuous aerosol generation with a mean flow rate of 4 L/min ($6.67{,}10^{-5}$ m^3/s), equivalent to a person sneezing, with the largest number of particles with diameter about 4 μm ± 1μm and concentration of approximately $1.2x10^6/cm^3$, according to (Duguid, 1946). The size and concentration of the generated particles were constantly monitored. This procedure is of fundamental importance to guarantee that all tests were performed with the same amount and concentration of particles generated and injected into the cabin environment. The particle measurement was performed with an optical particles counter Met One, which has six channels for counting particles in the range of 1 to 10 μm (1 to 2 μm, 2 to 3 μm, 3 to 5 μm, 5 to 7 μm, 7 to 10 μm, and greater than 10 μm).

Similar to the procedure implemented by (Wan et al., 2005 and Fabichak Jr et al., 2014), the particles were injected by simulating passenger seated, respectively, near the fuselage and near the aisle at the end of the mock-up, measuring the concentration of particles at the height of 1.10 m from the floor (breathing zone) in all other seats, as shown in Figure 4.



a) *b)*

Figure 4. a) Measurement points of particles in the mock-up and injection points at seats 3A and 3B
b) Heated manikin and particle counter

3. RESULTS AND DISCUSSION

Initially, are shown the results of the measurements of air velocities and temperatures, and respective analysis of the air flow pattern and of the differences in air temperatures along the cabin, in each of the both ventilation systems (MV and DV).

Afterwards, with the aim of performing a comparative analysis of the results for each ventilation system, the results of particle concentration and the analysis of the dispersion and removal of particles at the breathing region are presented. The velocity and air temperature results are presented in the form of profiles and those of particle concentrations in bar graphs.

3.1 Air Velocity (Profiles)

Figure 5 shows the air velocity profiles for the MV and DV ventilation systems. It is important to point out that positions 1C, 2C and 3C correspond to the aisle region. In these seats the highest height corresponds to 1.60 m, because this is the aisle and 1.6 m would be closer to a breathing height of a standing person

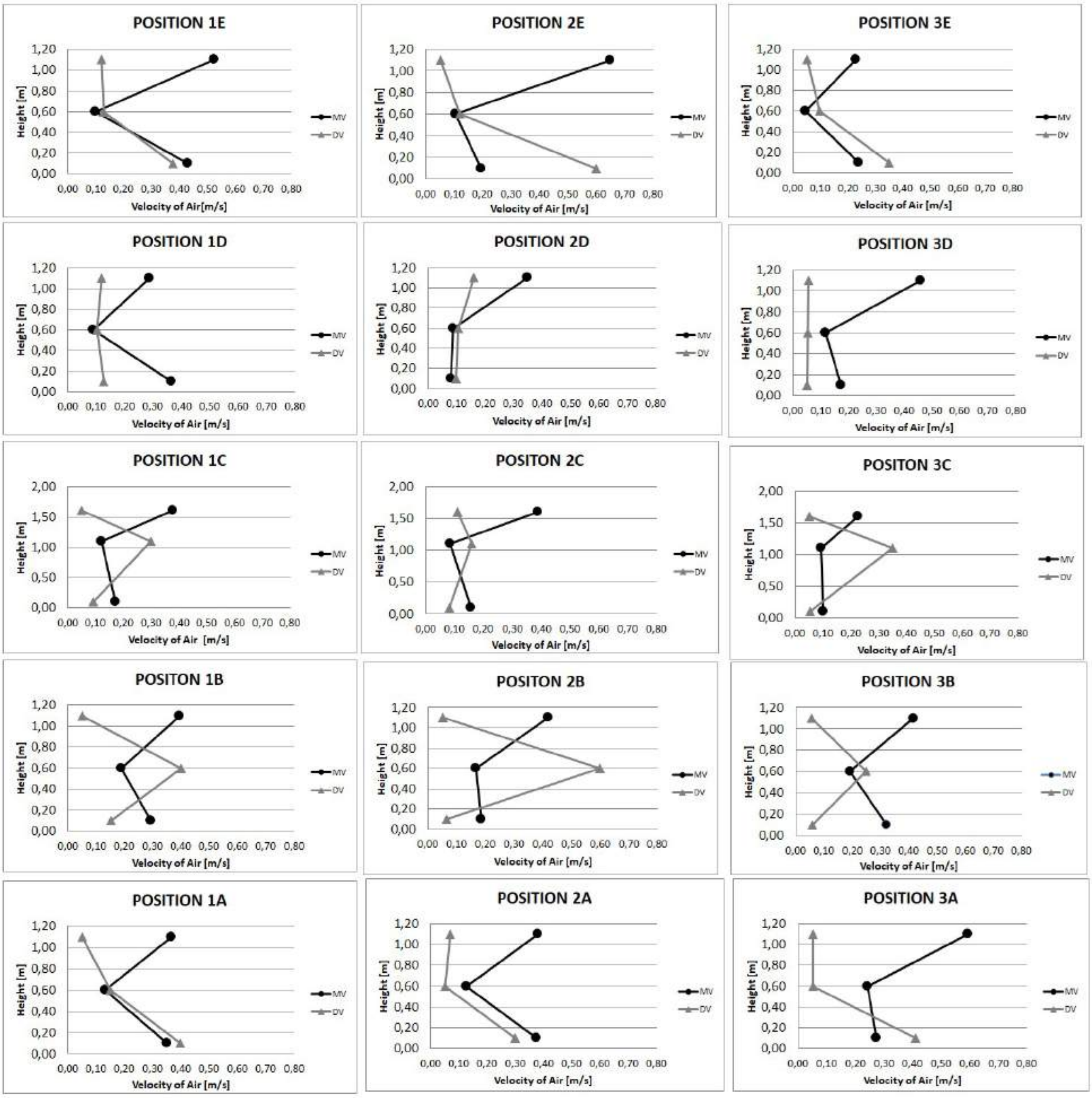


Figure 5. Air velocity profiles for ventilation systems MV and DV.

In the analysis of Figure 5 it can be verified, in the region of the seats, that:

a) air velocity profiles for the MV system present higher velocities in the head region, near the air inflation area, with reduction in the thigh, hands and forearms, increasing again in the region of the feet.

b) the DV system features larger air velocities in the region of the feet for seats next to the fuselage and an increase in air velocities in the region of the thighs, hands and forearms for seats along the aisle.

It is important to emphasize that similar behaviour of the air velocity profiles (Fig.5) was also verified for the MV system in a numerical simulation work developed by Zhang and Chen (2007) and for the DV system in an experimental work developed by Zhang et al. (2017).

3.2 Air Temperature (Profiles)

Figure 6 shows the air temperature profiles for the MV and DV ventilation systems.

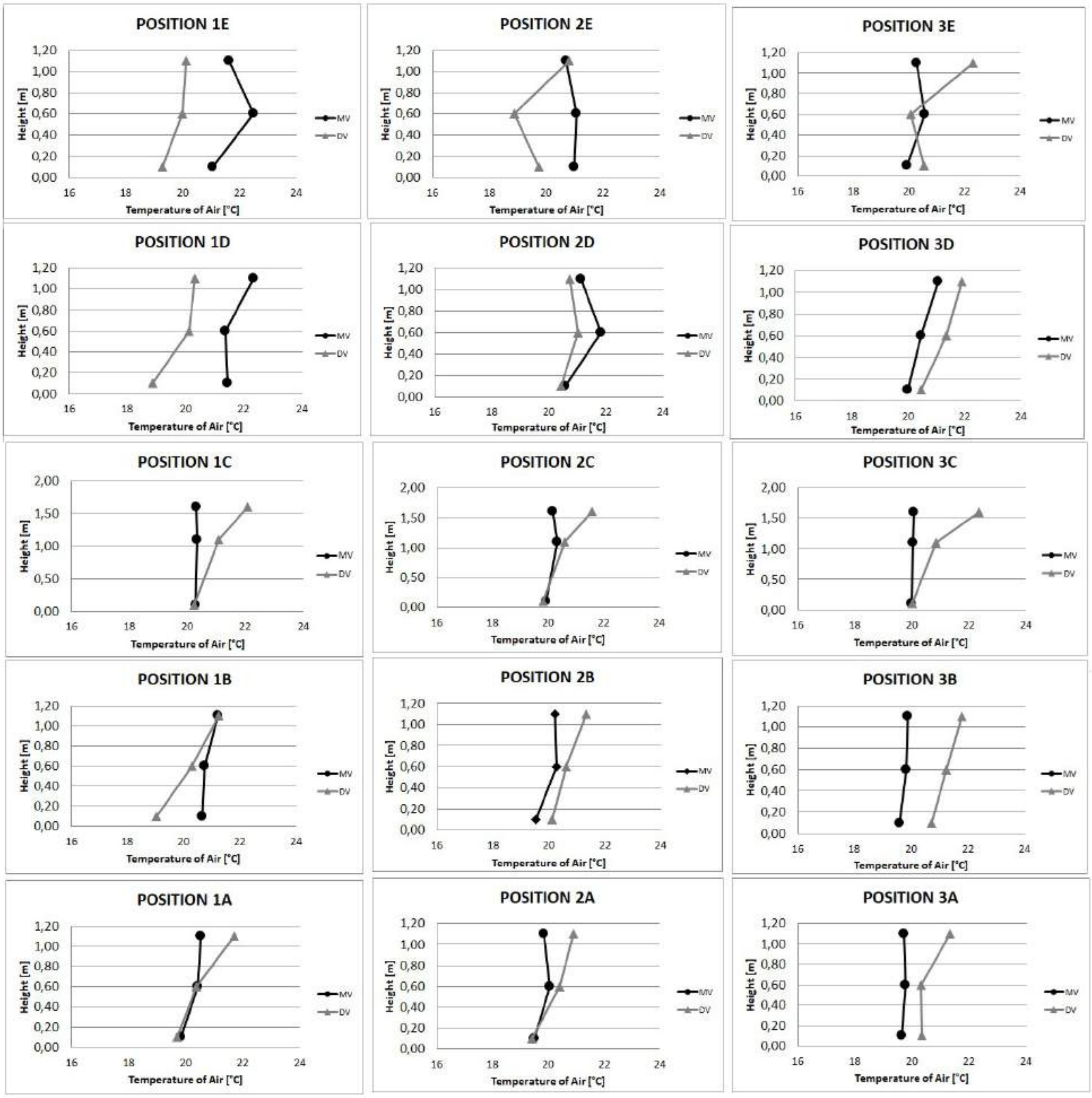


Figure 6. Air temperature profiles for ventilation systems MV and DV

In the analysis of Figure 6, it can be verified that there is little temperature stratification with the height for the two ventilation systems. The maximum values of temperature difference between the feet and the head was of 1.4 ° C for the mixing system MV and of 1.6 ° C for the displacement system DV. The small variations found in the non-similarities between 1 A and 1 E seats, may be related to a normal temperature variation generated by the Heated manikins.

3.3 Concentration, Dispersion and Removal of Particles at the Respiration Region

The results of particle concentration for the MV and DV systems are presented in Figures 7 to 9 and Table 1. Results are presented for air supply temperature of 18 ° C considering injection/generation of particles at seats 3A and 3B, respectively.

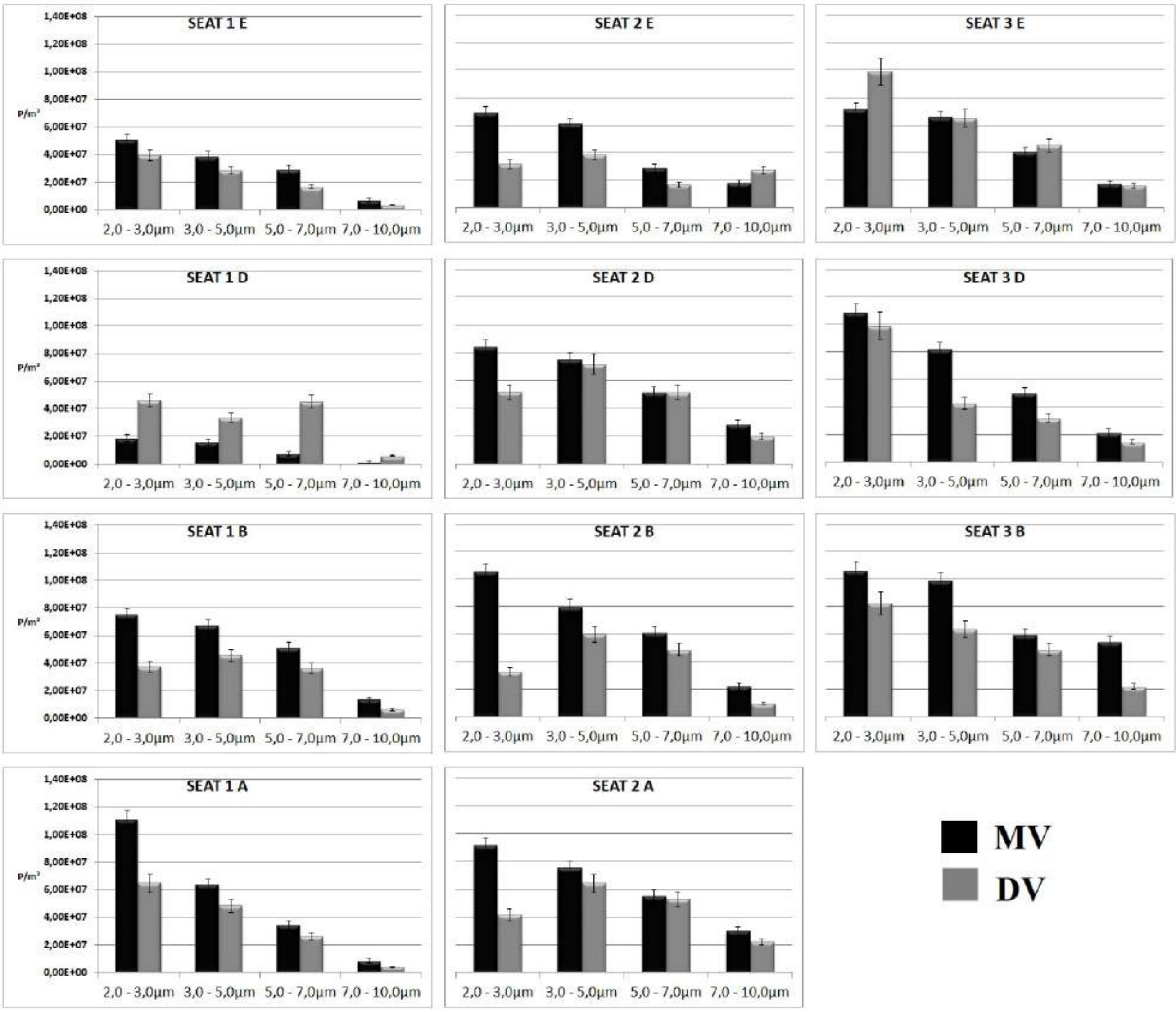


Figure 7. Concentration of particles with injection of particles by the seat 3A.

- Analysis of the concentration and dispersion of particles with respect to the point of injection/generation of particles

The results presented in Figures 7 to 9 and in Table 1 show a larger dispersion of particles, with an increase in the concentration of particles in the breathing zone, when the injection of particles is performed at the seat 3B in comparison with the injection at seat 3A, in both ventilation systems MV and DV.

This fact was also observed by Wan et al. (2005), in a mock-up MV tests with 21 seats (three rows of seven seats). According to these authors, in the MV system the downward airflow near the fuselage, with exhaustion near the floor, suppresses the dispersion of particles, while the upward flow in the center of the mock-up increases the dispersion of particles. In the case of the DV system the result is similar, although the phenomena involved are quite different. In the DV system there is an upward flow of air, with greater removal of particles near the wall due to the greater air exhaustion in this region of the mock-up (60%).

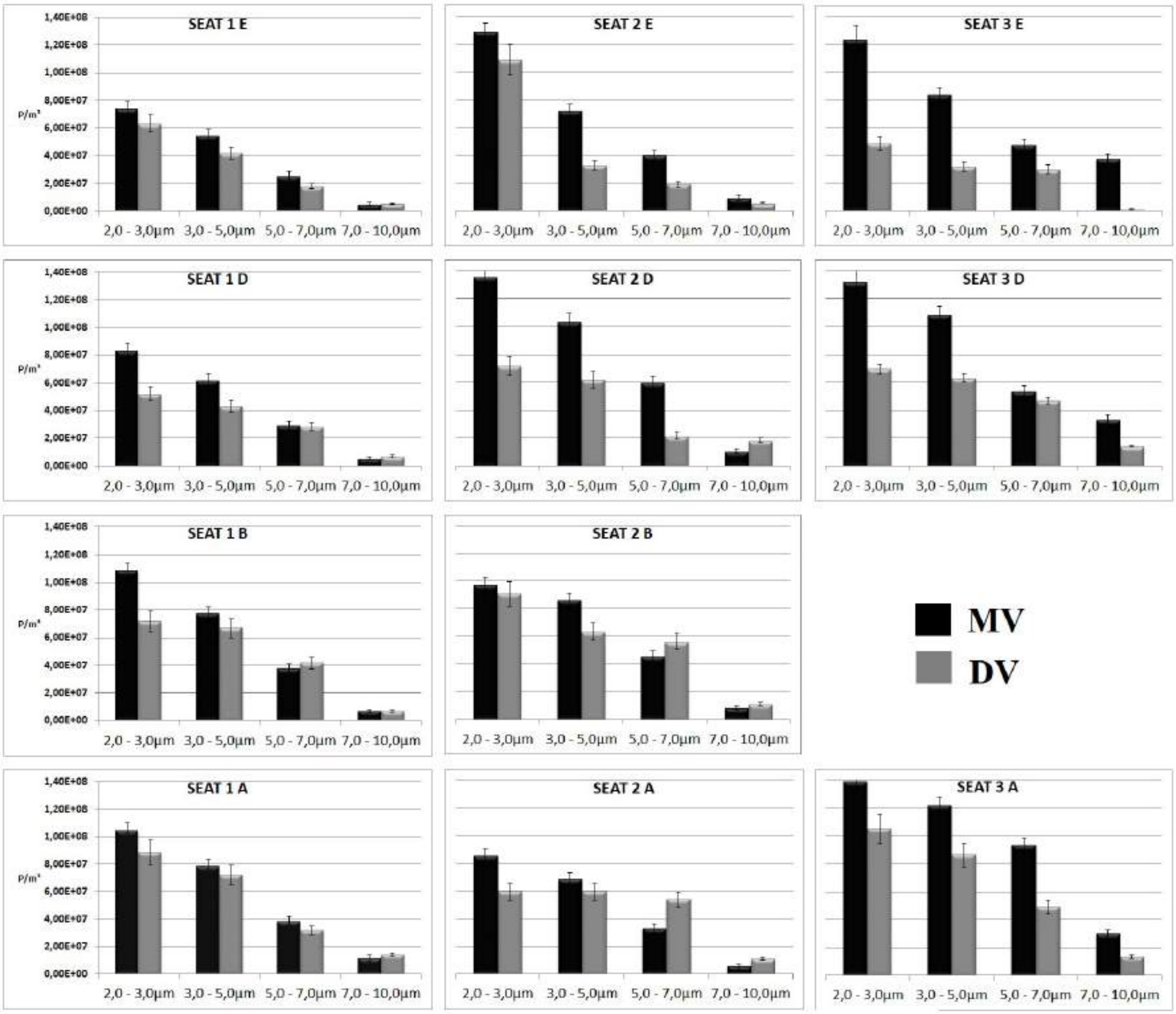


Figure 8. Concentration of particles with injection of particles by the seat 3B.

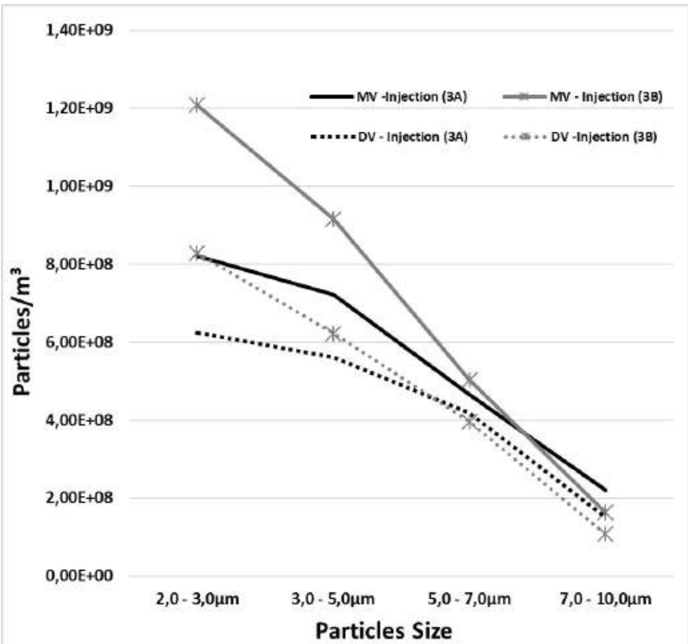


Figure 9. Total particle concentration in the mock-up for MV and DV ventilation systems with particle injection, respectively, at seats 3A and 3B.

Table 1. Total particulate concentration in the mock-up for MV and DV ventilation systems with particle injection, respectively, at seats 3A and 3B.

MV (System)/				
Size Particles	**2.0 – 3.0µm**	**3.0 – 5.0µm**	**5.0 – 7.0µm**	**7.0 – 10.0µm**
Injection (3A) [P/m³]	8.21E+08	7.21E+08	4.67E+08	2.20E+08
Injection (3B) [P/m³]	12.11E+08	9.16E+08	5.03E+08	1.63E+08
DV (System)				
Injection (3A) [P/m³]	6.25E+08	5.61E+08	4.19E+08	1.51E+08
Injection (3B) [P/m³]	8.29E+08	6.22E+08	3.96E+08	1.07E+08

-Analysis of the removal of particles in the respiratory region in relation to the ventilation system

As shown in Figures 6 to 9 and Table 1, the MV system presents less particle removal for both large and small particles. The lowest removal of particles from the breathing region in the MV system in relation to the DV system is due to the downward flow of air in the MV system, which makes it difficult to drag the particles to the cabin exhaust, especially the smaller, lighter ones suspended in the air.

In order to evaluate the potential of the DV system in the removal of particles in the respiratory region, percentages of particle removal from the DV system were calculated with respect to the MV system by means of Equations 1.1, DV / MV, presented in Tables 1.2, such as:

$$DV/MV = \frac{(MV-DV)}{MV} \quad (1.1)$$

MV = concentration of particles in the MV system (P/m³)

DV = concentration of particles in the DV system (P/m³)

From the analysis of Table2, it can be verified that the DV system presents the greatest efficiency in the removal of particles with a supply air temperature of 18 ° C.

The smaller amount of particles in the breathing region observed with the DV system is a function of the upward movement of the air and a greater effect of the thermal plumes generated by people heat transfer, notably in the smaller particles more easily dragged by the upward movement of the air.

Table 2. Particle removal efficiency for DV system with respect to MV system

Efficiency of particle removal (%)				
Temperature Air Supply of 18 °C	**Size Particle**		**2.0 - 3.0 µm**	**3.0 - 5.0 µm**
	DV/MV	**Injection 3A**	23,9	22,3
		Injection 3B	31,4	32,0

4. CONCLUSION

The particulate injection/generation point and the ventilation system have a large influence on the concentration, dispersion and removal of particulates in the breathing region along the mock-up in the two ventilation systems (MV and DV).

The results showed that the DV system can be used successfully in aircraft cabins regarding dispersion and effectiveness in removal expiratory droplets. In the present study the DV system compared to the conventional system MV reduced the dispersion of particles along the cabin and increased the removal of particles up to 31,4 % for particles of 2 to 3µm, and up to 32,0 % for particles of 3 to 5 µm. This analysis was performed for this particle size because more particles in respiratory activity are generated at this specific size. Smaller particles are more likely to reach deeper into the respiratory system.

Finally, it is important to emphasize the greater efficiency of the DV system in removal smaller particles compared with the MV system. It is particularly important since smaller particles are easily inhaled and can cause serious health problems.

5. ACKNOWLEDGEMENTS

DFJ acknowledges the Coordination for the Improvement of Higher Level Personnel - CAPES for his scholarship.

6. REFERENCES

ANSI/ASHRAE Standard 161. Air Quality Within Commercial Aircraft. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, 2007

Bosbach, J., Heider, A., Dehne, T., Markwart, M., Gores, I., Bendfeldt, P., Evaluation of cabin displacement ventilation under fight conditions. *ICAS*, Brisbane, 2012

Chen Q, M.C, Devitt J.J, Gupta J.K, Jones B.W, Mazumdar, S., Poussou S.B., Infectious disease transmission in airliner cabins. Report No. RITE-ACER-CoE-2012-1. Auburn, *USA: National Air Transportation Center of Excellence RITE/ACER*, 2012.

Conceição, S. T., Air contamination in air-conditioned cabins: Evaluation process and analysis of the influence of personalized ventilation system. *PhD thesis*. Department of Mechanical Engineering, Polytechnic School, São Paulo, 218p (in Portuguese), (2012).

Duguid, J. P., The Size and the Duration of Air-Carriage of Respiratory Droplets and Droplet-Nuclei, J. Hyg. 44:471–479, 1946.

Fabichak Jr, D; Souza da Silva, E ; Tribess, A. Influence of mixing ventilation and underfloor air distribuition on the dispersion of expiratory droplets in aircraft cabin: An experimental analysis. In: *Proceedings of Roomvent* 2014, 2014, São Paulo. Helsink: SCANVAC,. p. A-10, 2014.

Fiser, J., Miroslav, J., Impact of air distribution system on quality of ventilation in small aircraft cabin. *Building and Environment Technická* 2896/2, 616 69 Brno, Czech Republic, 2013.

Gao, N.P. Niu, J.L., Perino, M. Heiselberg, P., The airborne transmission of infection between flats in high-rise residential buildings: Tracer gas simulation, *Building and Environment* 43: 1805–1817, 2007

Gupta, J.K., Lin, C.H., Chen, Q., 2011, Transport of expiratory droplets in an aircraft cabin, Indoor Air; 21: 3–11 , 2011

Li, F., Liu, J., Pei, J., Lin, C.-H.,and Chen, Q., Experimental study of gaseous and particulate contaminants distribution in an aircraft cabin. *Atmospheric Environment:* vol 85, 223-233, 2014.

Mangili A., Gendreau, M.A., Transmission of infectious diseases during commercial air travel. *Lancet*; 365: 989–96, 2005.

Olsen S.J., Chang H.L., Cheung T.Y., Transmission of the severe acute respiratory syndrome on aircraft. New England *Journal of Medicine*, 349, pp. 2416–2422, 2003.

Pang L, Xu J, Fang L, Gong M, Zhang H, Zhang Y. Evaluation of an improved air distribution system for aircraft cabin. *Building and Environment*; 59(1):145-152, 2013

Sze To, G.N., Wan, M. P., Chao, C. Y. H., Fang, L. Melikov, A. Experimental Study of Dispersion and Deposition of Expiratory Aerosols in Aircraft Cabins and Impact on Infectious Disease Transmission', *Aerosol Science and Technology*, 43(5): 466 — 485, 2009

Volavý, J., Fiser, J., Nöske, I., Prediction of air temperature in the aircraft cabin under different operational conditions. *EPJ Web of Conferences* 45 01096 , 2013.

Wan, M.P., Chao, C.Y.H., Fang, L., Transmission characteristics of passenger-exhaled droplets in a simulated air-cabin environment. *Proceedings of Indoor Air,* 2005.

Wan, M. P., Sze To, G.N., Chao, C. Y. H., Fang, L. Melikov, A., Modeling the Fate of Expiratory Aerosols and the Associated Infection Risk in an Aircraft Cabin Environment', *Aerosol Science and Technology*, 43(4): 322-343.(2009)

Yan, W., Zhang, Y., Sun, Y., Li, D., Experimental and CFD study of unsteady airborne pollutant transport within an aircraft cabin mock-up. *Building and Environment* 44:34–43, 2009

You,R., Chen, J., Shi, Z., Liu, W., Lin, C.-H.,Wei, D.,and Chen, Q., Experimental and numerical study of airflow distribution in an aircraft cabin mockup with a gasper on. *Building performance simulation, 2016*

Zhang T., Chen Q., Novel air distribution systems for commercial aircraft cabins. *Building and Environment* (42):1675-1684, 2007

Zhang Z., Chen X., Mazundar S., Zhang, T. Chen, Q., Experimental and numerical investigation of airflow and contaminant transport in an airliner cabin mock-up. *Building and Environment*, 44(1): 85-94, 2009

Zhang Y, Liu J, Pei J, Li J, Wang C. Performance evaluation of different air distribuition systems in an aircraft cabin. Aerospace Science and technology. 70 359-366, 2017

7. RESPONSIBILITY NOTICE

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.