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NUMERICAL SIMULATION OF VENTILATION IN SUBWAY CAR USING CFD OPEN-SOURCE CODE

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Abstract. *The pandemic caused by Coronavirus in 2019 brought the world's attention to biosecurity. Due to the rapid growth of city population and expansion of cities, people are now living further than ever from their workplaces, and underground infrastructure became the solution for an overly crowded urban mesh. This scenario results in intense and prolonged use of underground public transportation systems, such as the subway. At the beginning of the SARS-Cov-2 spread, many measures concerning social distancing and sterilization were taken, but the most efficient and effective way to prevent aero transmissible diseases is by improving the ventilation of the space. The aim of this research is the study of the ventilation and air renovation inside surface trains and subway cars. To this end, CFD simulation (Computational Fluid Dynamics) was carried out in OpenFOAM, an eulerian mesh-based software. As a result of the complex geometries inside train cars and the unique distribution of elements inside the train that affect airflow, such as seats, doors and in and outlets, each case has its own particularities. Using CFD tools properly, it is possible to locate recirculation zones inside the car, which can be dangerous as potential contamination places for airborne diseases, and areas that can reach extreme temperatures given poor air distribution. 2D simulations were carried out based on geometrical and operational conditions observed in cars from subway and trains of São Paulo, Brazil. Furthermore, it is expected that results obtained from CFD simulations can serve as basis and help with decision making in ventilation projects, as this type of methodology is less financially expensive when compared to experimental methods, and can capture in more detail complex phenomena.*

Keywords: *computational fluid dynamics (CFD), indoor air quality, ventilation.*

1. INTRODUCTION

During the COVID-19 pandemic, the public transportation sector experienced significant changes in demand worldwide (Qiu et al., 2020). Passengers' major concern is the risk of COVID transmission, as it primarily occurs through the air in enclosed and densely occupied spaces (World Health Organization, 2021). Consequently, during the peak of the pandemic, several measures and studies were undertaken to reduce the contamination rate in these environments (Gkiotsalitis and Cats, 2020; Zheng et al., 2020). These measures included social distancing, mask-wearing, hand sanitization, and increased cleaning of buses and trains (Shen et al., 2020). Additionally, proposals were made to reduce passenger congestion and waiting time at transfer points by synchronizing vehicle arrivals and departures with the expected arrival times of higher passenger numbers (Gkiotsalitis and Cats, 2020; Ceder, 2016; Yap et al., 2019; Gavriilidou and Cats, 2019; Vansteenwegen and Van Oudheusden, 2006; Wong et al., 2008). Limiting passenger numbers and imposing the maximum vehicle occupancy were also suggested to control crowding (Delgado et al., 2009).

These measures effectively reduced the risk of transmission by reducing the number of crowded passengers or the time they spent in close proximity. However, there is a strong relationship between occupancy and air quality. The reduction in passengers and social distancing can effectively decrease the contamination risk only when implemented alongside improved ventilation in the environment (Sun and Zhai, 2020). Such measures enhance biosafety not only regarding COVID-19 transmission but also other airborne viral, bacterial, and fungal diseases (Fujii, 2006). It has been observed that a significant number of higher-income public transportation users have stopped using it during the pandemic and sought alternative means of transportation (Hernandéz, 2020). Therefore, enhancing biosafety in public transportation is not only a health issue but also a matter of social equality.

In São Paulo, Brazil, the subway system carries approximately 50 million passengers per month (data from April 2022), with daily peaks exceeding 2 million (Portal da Transparência). However, in May 2020, one of the pandemic peaks, the total number of passengers transported was around 20 million. The trend is now returning to pre-pandemic habits, including the use of public transportation and the resumption of in-person education and work. Nevertheless, biosafety in public transportation has always been a concern even before the COVID-19 crisis emerged.

Due to high demand and occupancy rates, along with the large number of passengers and diversity of origins, subway cars and buses are environments where airborne diseases can easily spread, especially in cases of insufficient ventilation to maintain ideal air quality. For this reason, to prevent passenger contamination and the emergence of new pandemics and epidemics, it is essential to understand the ventilation systems in such environments.

Computational Fluid Dynamics (CFD) simulations offer a method to study and comprehend air behavior with precise results and diminished financial costs. In the case of the subway, numerous studies using CFD have been conducted (Peng et al., 2021; Camelli et al., 2017), achieving results consistent with expectations and experimental data. However, due to the variety of different models, operation modes (velocity, occupancy, temperature, humidity), ventilation techniques, and types of subway cars used worldwide, results may vary and cannot be universally applied to all subway systems. Therefore, to understand the ventilation system of a specific line, a study considering defined norms and characteristics and understanding the peculiarities of the environment would be necessary.

2. CASE STUDY

For the study of ventilation inside train and subway cars, the CPTM (Companhia Paulista de Trens Metropolitanos) series 8500 gangway type trains were chosen due to the ease of access to information about this series by the authors and the number of cars of this series currently in circulation. The series 8500 trains are composed of 8 cars, symmetrically arranged and directly connected to each other without partitions between them. Their configuration and main dimensions can be seen in Figure 1.

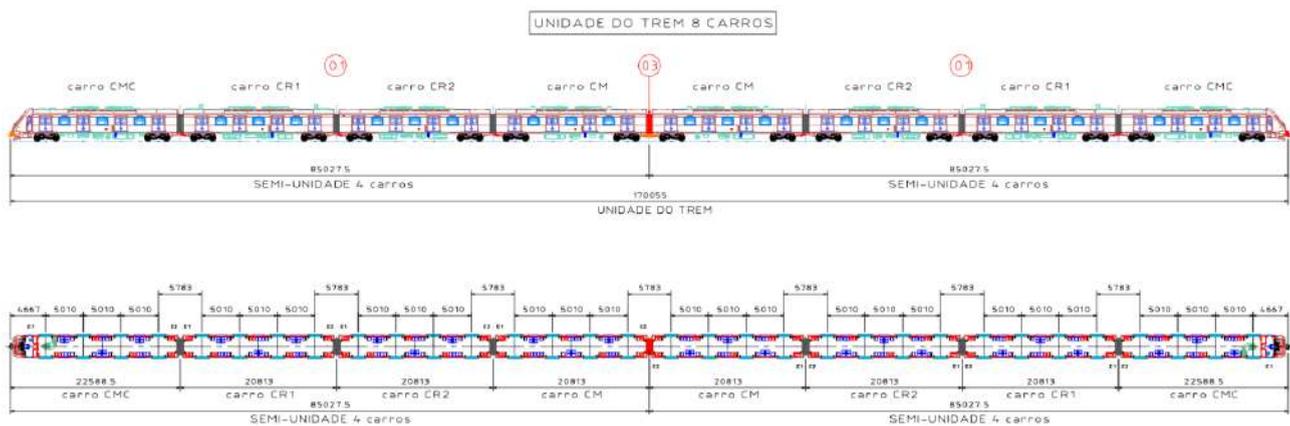


Figure 1. Layout of the cars in the train - open-wide gangway 8500 series.

Thus, the authors visited two CPTM workshops, the CPTM Oficina de Manutenção - Abrigo Engenheiro SP and the Oficina Roosevelt, both located near the Carrão neighborhood in São Paulo, to perform on-site measurements related to the air outlets. During the visit, the wagon model could be studied in more detail, as well as the ventilation and temperature control systems in operation.

In the first workshop, a car of this model could be seen operating. The passenger compartment's ventilation system operates separately from the one in the driver's cab, consisting of an air conditioning compartment with cooling and air intake for renewal. In the series 8500, there is an air volume exchange of 30 to 50% for renewal, and temperature control and air conditioning are automated, controlled by the data bus, in order to always ensure that the temperature difference between the internal and external air is less than 5°C, avoiding thermal shock. Thus, the air conditioning in the passenger compartment normally operates at 21°C with an increase or decrease of 25% of this temperature.

A photo of the model taken in the first workshop, and the facilities of the location, can be seen in Figure 2.



Figure 2. Visit to the Abrigo Engenheiro CPTM workshop: train car (left) and ventilation system (right).

In the second workshop, where repairs to the systems that compose the train car are performed, the authors were able to observe a disassembled air conditioning and cooling system. A calibrated system was used to measure the air outlet velocity, which was employed in the preliminary simulations. Images from the visit and the air outlet velocity measurement can be seen in Figure 3.



Figure 3. Visit and measurements in Oficina Roosevelt workshop.

The general dimensions and outlet air-conditioning system velocity of the 8500 series car is used as the basis for the simulations conducted for this preliminary study.

3. NUMERICAL SIMULATION

In this study, the main objective was to obtain preliminary information about the air behavior inside a simplified train or subway car, with dimensions based on the model of the CPTM series 8500 gangway. The measurements used are represented in Figure 4. It can be observed that the geometry is highly simplified, without any obstacles such as safety bars, seats, doors, or passengers. In these preliminary simulations, only the air behavior in the "empty" car and the impact of the air outlet direction from the air system on its distribution throughout the space were studied.

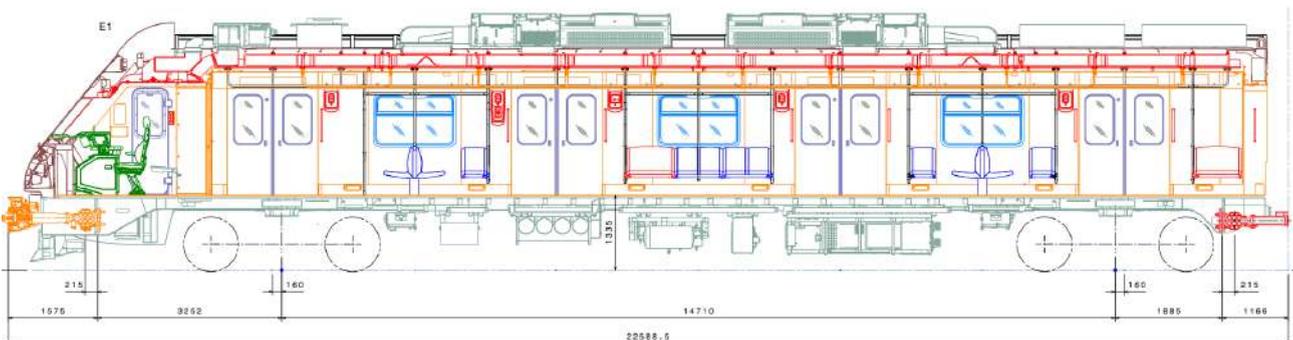


Figure 4. General dimensions of the open-wide gangway 8500 series.

3.1 Geometry

Three distinct two-dimensional geometries were simulated, each representing a portion of the train car. The series represented in the study is of the open-wide gangway type, with no division between the cars, which improves the ventilation of the passenger compartment. Even in case of ventilation and renewal system failure, the accelerated motion of the car generates internal air movement.

For the first geometry, only one car of the entire train was represented. The simplified geometry can be seen in Figure 5.

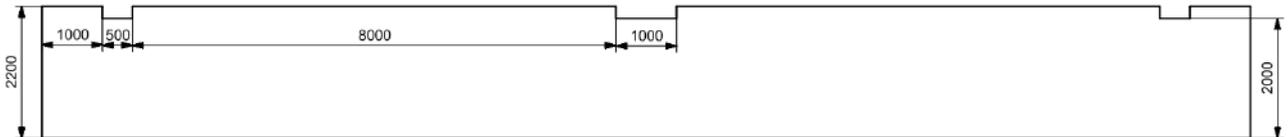


Figure 5. Simplified geometry for one car (in millimeters).

For the second geometry, two cars were modeled, in order to obtain information about what happens in the gangway between the two cars. The simplified gangway was modeled with 1 meter in length and 2 meters in height. The third geometry was made to represent three adjacent cars.

3.2 Mesh

The convergence simulations conducted indicated that the residual was sufficiently small for grid element size 0.05 meters. Those results are shown in 4.1. Therefore, all case meshes were made with regular elements of dimensions 0.05x0.05 meters. Those can be seen in Figures 6 to 8.

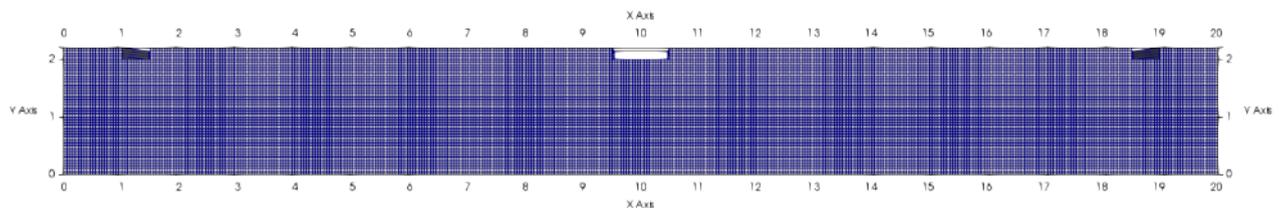


Figure 6. Mesh for one car.

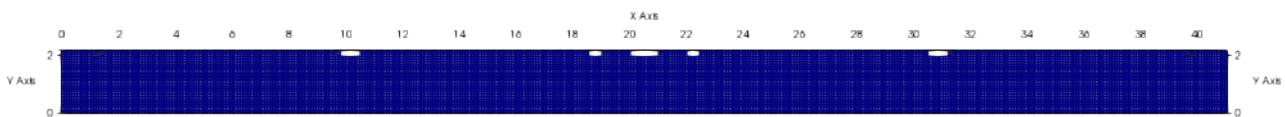


Figure 7. Mesh for two cars.



Figure 8. Mesh for three cars.

3.3 Boundary conditions

Three configurations of air inlet were used through the ventilation outlet, represented by a rectangle in the center of the car. For future simulations, the entire air circulation system, including internal grilles and air intake locations, will be modeled in three dimensions. However, for this study, the focus was on the difference between the directions of air outlet for renewal and recirculation zones.

For the first configuration of flow direction grilles, the flow is directed downwards directly, as shown in the schematic representation in Figure 9 (left).

In the second configuration, the flow is laterally directed only, without any vertical component in its outlet velocity. This outlet condition is schematically represented in Figure 9 (right).

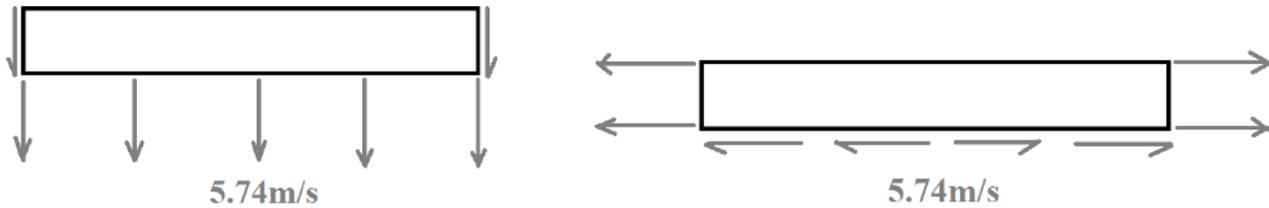


Figure 9. Inlet configurations 1 (left) and 2 (right).

In the third configuration, the flow is a combination of the two previous ones, represented in Figure 10, with the resultant velocity component of 5.74 m/s divided into two equal components of value 4.06 m/s each.

The air inlet areas where the previously mentioned velocities are imposed are the same in all three cases, ensuring that the flow rate is constant in the study and that the change in air distribution depends solely on the direction of velocity. The value of the air inlet velocity used is the one measured in the CPTM workshop, as seen in the anemometer in Figure 3.

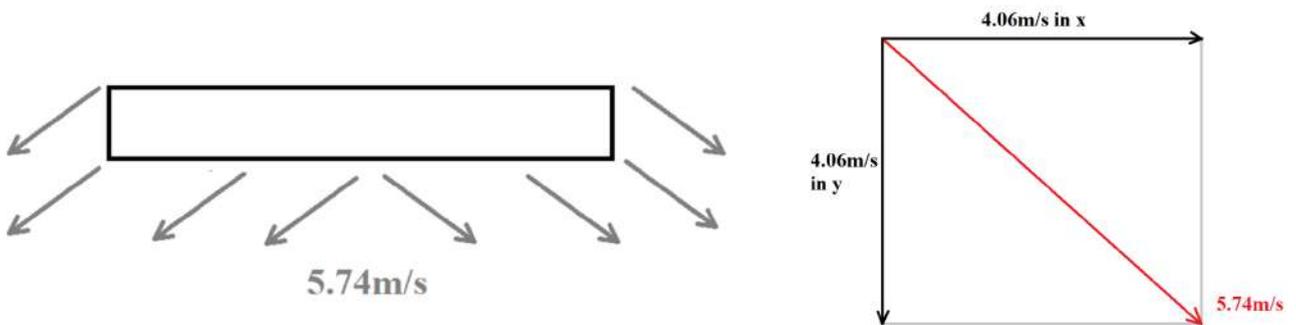


Figure 10. Inlet configuration 3.

At the gangway outlets, a wall boundary condition was applied, as well as on the floor and ceiling where there is no air inlet or outlet. At the air outlets, an atmospheric pressure condition was imposed. These conditions are represented in Figure 14.

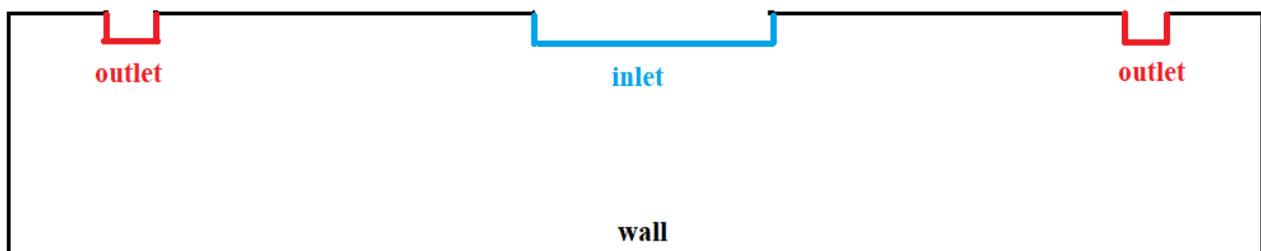


Figure 14. Boundary conditions for the simplified car.

3.4 Numerical method

The simulations were conducted using OpenFOAM, an open-source Computational Fluid Dynamics (CFD) tool, with an Eulerian finite volume method on meshes. The air was considered an incompressible, perfect homogeneous Newtonian fluid due to its low velocities.

Laminar flow hypothesis was assumed, as it is expected to have minimal energy loss due to turbulence, thus no empirical turbulence modeling was used.

Under these conditions, the IcoFoam solver was chosen for the simulations, which solves cases of low-turbulence flow of incompressible fluids at low velocities using continuity and Navier-Stokes equations, presented below.

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial(u_i u_j)}{\partial x_j} = - \frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i} \left(\mu \frac{\partial u_i}{\partial x_j} \right) + f_i \quad (2)$$

Where u is the velocity component, t is time, ρ is the mass density, p is the pressure, μ is the dynamic viscosity, and f represents possible external forces.

4. RESULTS

4.1 Convergence

The convergence cases were simulated using the hybrid inlet configuration (with non-zero velocity components in both directions) with maximum values in the components (5.71 m/s in x and y directions). The outlets were set to have zero static pressure, aiming to maximize the velocities in the control volumes and, consequently, the Courant number. The maximum residual values were obtained for meshes with three different refinements, featuring regular square mesh elements with dimensions of 0.1, 0.05, and 0.025 meters. The time step sizes were adjusted as well, in order to keep the Courant number below 1.

The maximum residual value, considering simulation time and domain dimensions, obtained for the mesh with element size 0.05, was deemed acceptable, and all the subsequent simulations were conducted using meshes with regular square elements of size 0.05.

4.2 One car

The following results were obtained for the three inlet configurations, for the instants 5, 10, 15 and 20 seconds, shown in Figure 15. They show qualitatively the impact the direction of the airflow inlet makes in air distribution inside the train car, which can be increased when other elements in the geometry are considered, such as chairs and passengers.

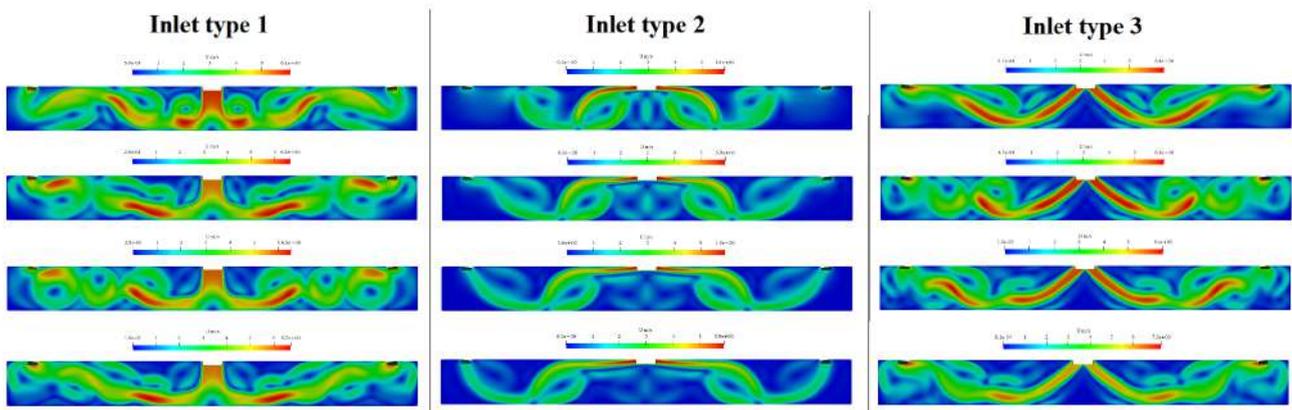


Figure 15. Velocity fields for different inlet configurations at 5, 10, 15 and 20 seconds.

4.3 Two cars

Data was also obtained from simulating two consecutive cars, and the velocity fields are shown below for time 20 seconds in Figures 16 to 18.

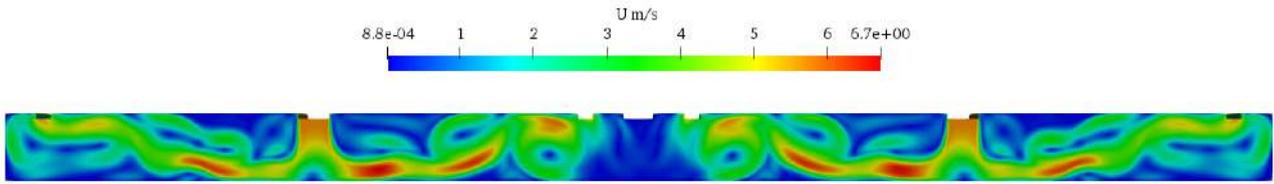


Figure 16. Velocity field for inlet type 1 in two consecutive cars.

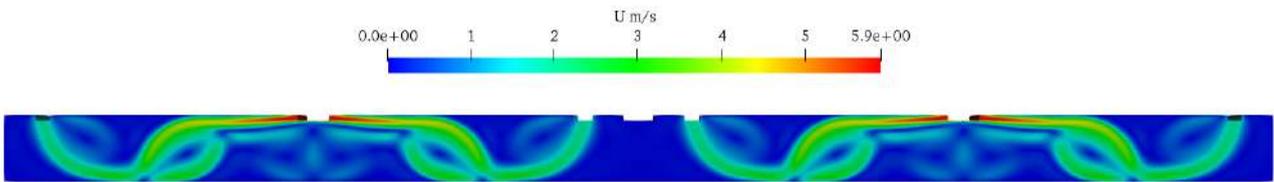


Figure 17. Velocity field for inlet type 2 in two consecutive cars.

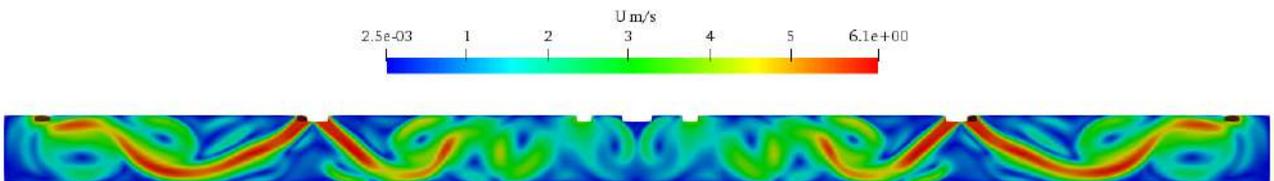


Figure 18. Velocity field for inlet type 3 in two consecutive cars.

4.4 Three cars

Simulations were conducted for three consecutive cars, and the velocity fields are shown below for time 20 seconds in Figures 19 to 21.

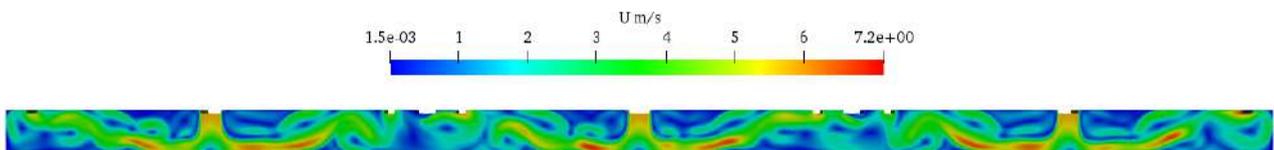


Figure 19. Velocity field for inlet type 1 in three consecutive cars.

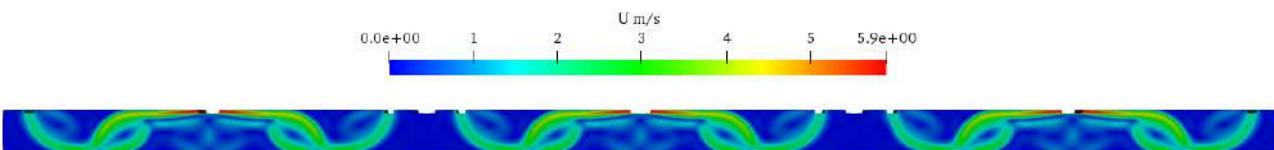


Figure 20. Velocity field for inlet type 2 in three consecutive cars.

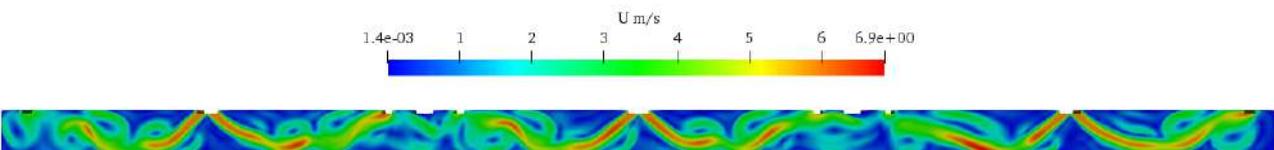


Figure 21. Velocity field for inlet type 1 in three consecutive cars.

5. DISCUSSION AND CONCLUSIONS

5.1 Airflow inside the cars

From the results shown in 4 it can be concluded that, while the first inlet configuration provides better air circulation in the center of the passenger cabin, it does not offer enough air circulation in the edges of the car. The second inlet configuration however can make the renewed air spread to further corners of the car, but only above the height of 1.5 meters, not being able to attend to the demands of people who are seated, for example.

The third inlet configuration combines both the capacity to spread renewed air and to direct it to the bottom of the car, assuring distribution throughout the entirety of the car.

Further work will focus on modeling the entirety of the air conditioning system of the train car, and add more complex elements inside the car, such as passengers and safety bars, as well as doors, in order to determine where ventilation and air renewal is insufficient, and plan ways to solve the problem.

5.2 Airflow in the gangway

As shown in simulations made modeling two or three cars, the gangway area is not receiving the treated air coming from the inlets if used the second configuration of inflow. This could mean that the gangway area can be a potential space for airborne disease contamination.

Comparing the ventilation in the gangway in the three inlet configurations, it can be concluded that it is the area that is most affected by the configuration of the inlet of the air conditioning system.

5.3 Biosecurity

In order to evaluate the velocity and pressure profiles that reach the medium height of the standing and seated passengers, respectively, the following graphs were obtained in ParaView to y values of 1.75 meters (average standing passenger) and 1.2 meters (average seated passenger) to each of the inlet configurations. Those can be seen in Figures 22 to 24.

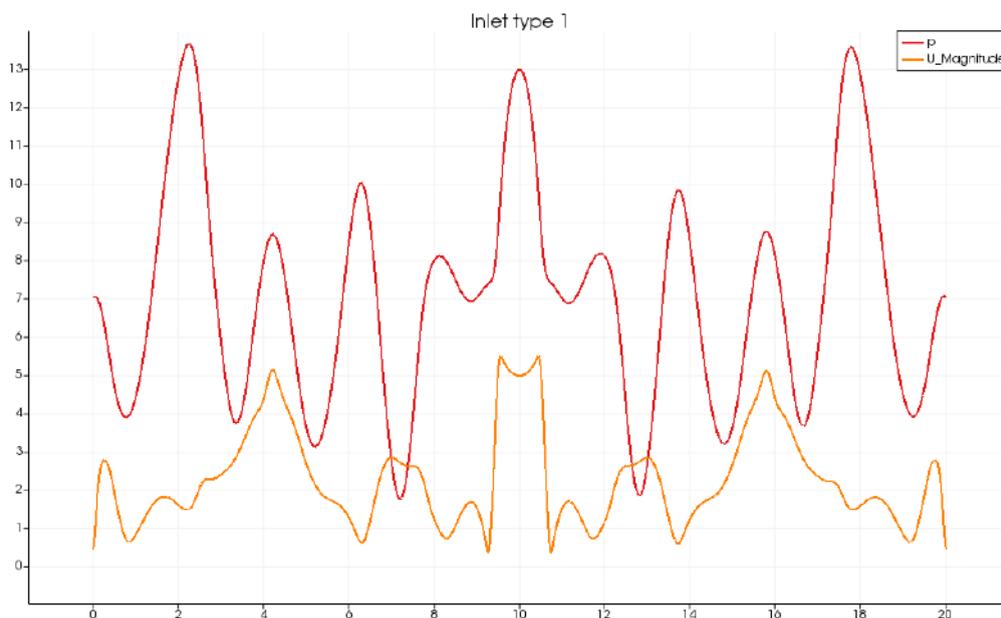


Figure 22. Velocity and pressure profiles over line at 1.75 and 1.2 meters high for inlet type 1.

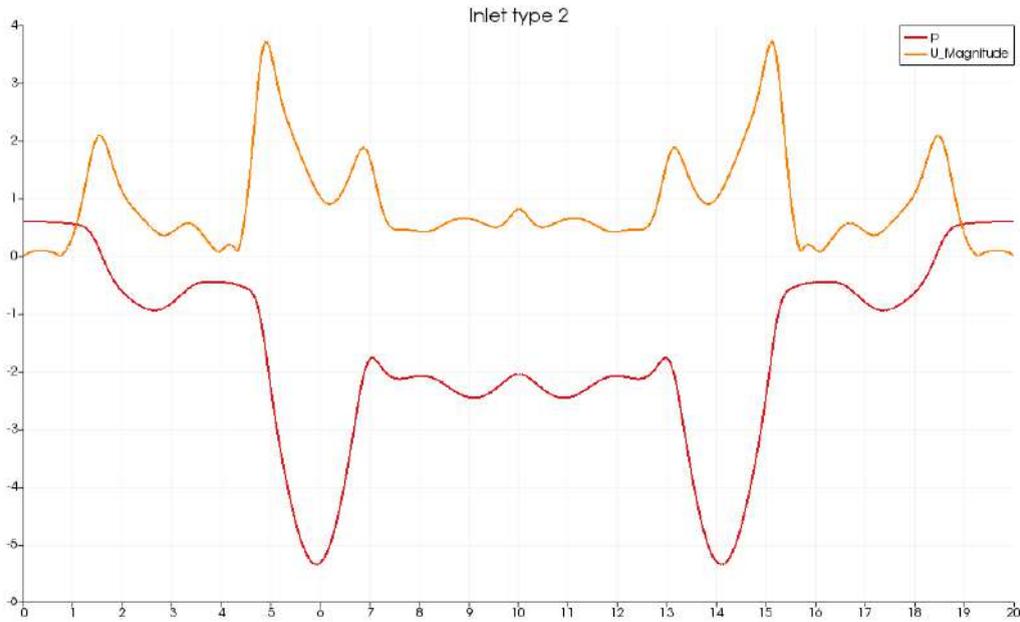


Figure 23. Velocity and pressure profiles over line at 1.75 and 1.2 meters high for inlet type 2.

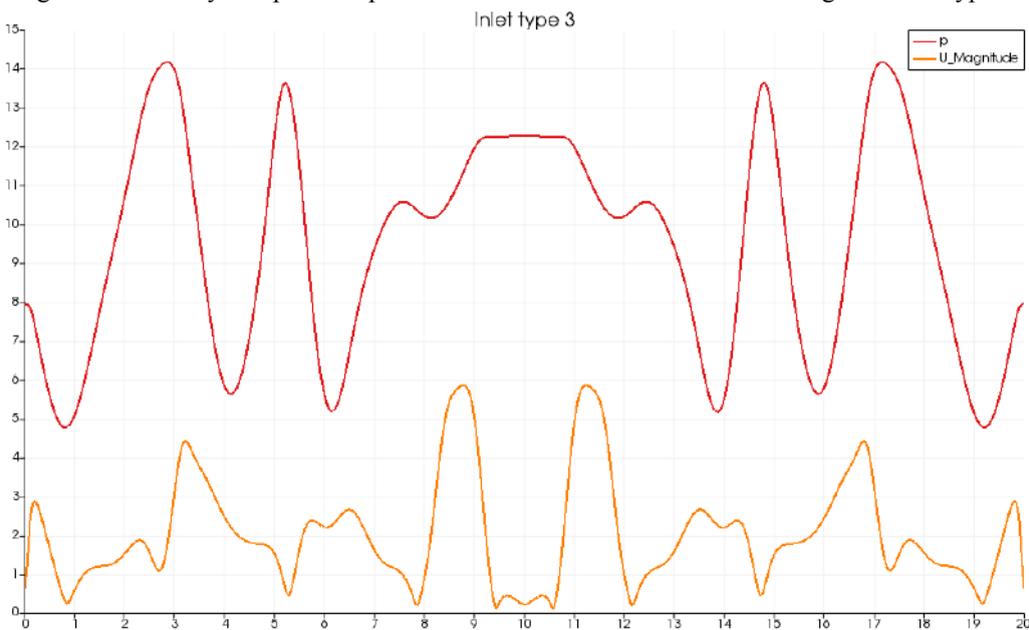


Figure 24. Velocity and pressure profiles over line at 1.75 and 1.2 meters high for inlet type 3.

As shown in the graphs above, the velocity magnitude is higher for seated passengers and for both seated and standing passengers in the corners of the car for the third inlet configuration. This means that the direction of the inlet velocity in air conditioning systems is critical for both comfort and biosecurity of users of the train system, and this data can help in designing and planning new air conditioning configurations.

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