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PARTICLE DISTRIBUTION ANALYSIS IN A CLEAN AIR ENCLOSURE WITH A KNOWN PARTICLE SOURCE

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Abstract. *Microdevices are getting even more popular with applications in many different areas such as medical, aerospace, communication, and others. A real challenge to manufacture and assembly of these devices is the needed cleanliness environment, which makes this facility expensive to maintain. These environments need a special air recycling system, in charge to clean the air from dust and to control the humidity, temperature, and pressure. The level of cleanliness of these environments is defined by ISO 14644-1, stipulating the concentration of contaminants per cubic meter. Due to the cost assigned to build a conventional clean room, the CEFET/RJ research group of Thermal Science in Micro and Macro Scale is designing a low-cost clean air enclosure system. This system is designed to achieve the level of cleanliness as class 100 (ISO5), making it possible to work safely with microdevices. This work aims to study the airflow and the contaminant distribution inside the designed clean air enclosure, considering a controlled particle source which could be, for instance, a manufacturing process. A sensitivity analysis is used to meet the requirements imposed by the standards and desire features to develop the suitable equipment to work with microdevices. The results provide the required airflow to provide the cleanliness level and other characteristics to generate the required airflow with low velocity inside the chamber.*

Keywords: *Microdevices; Cleanroom; Clean air enclosure; CONTAM; Particles concentration*

1. INTRODUCTION

The manufacturing and handling of microdevices demand an extremely clean environment usually known as the cleanroom. The cleanrooms are environments with a special air handling system, responsible to control the temperature, the humidity, and the concentration of particles per cubic meter. Such environments demand a high investment, both monetary and spacial. In order to solve this issue, the CEFET/RJ research group of Thermal Science in Micro and Macro Scale is designing a low-cost clean air enclosure system (Guerrieri and Nunes, 2019).

Similar systems are used in many other areas, such as the pharmaceutical industry and biosafety laboratories. All of these systems need to meet the ABNT (2019) standard where it determines the concentration of particles per cubic meter and defines the cleanliness level classes. The proposed clean air enclosure is designed to meet the class 100 (ISO5) requirement in the mentioned standard. Table 1 provides the concentration of the particles per cubic meter for each allowed particle size to meet the class 100 (ISO5) requirements.

Table 1. Concentration of particles per cubic meter for a Class100 (ISO5) as defined in ABNT (2019).

Particle diameter	Particles/m ³
≥ 5 μm	29
≥ 1 μm	832
≥ 0.5 μm	3520
≥ 0.3 μm	10200
≥ 0.1 μm	100000

This work explore the possibilities to implement the adequate air cleaning system, looking to the airflow types (laminar or turbulent), the velocity of the air inside the chamber, the effectiveness to clean the air enclosure system, and simulate the presence of particle sources, aiming to reach an optimum cleaning time. The CONTAM 3.2 is used to simulate the concentration of contaminants, and the influence of particle sources inside the system. The CFD-0 simulations show the airflow behavior inside the chamber and the contaminant dispersion generated by the contaminant sources, besides it is implemented a solution to reduce the airflow velocity.

The CONTAM 3.2 is free software provided by NIST (National Institute of Standards and Technology). The CONTAM software was developed to perform quality and ventilation analysis to determine airflow rates and pressures, for instance. The CFD-0 software is a computational fluid dynamics tool developed by Srebric *et al.* (1999) and improved by Wang (2007) used to complement the CONTAM model. The tool solves the partial differential governing equations from the mass, momentum, energy, and species conservation theory by numerical means, besides the use of the Reynolds Averaged Navier-Stokes (RANS) method when applying the turbulence models (Wang and Chen, 2007). The CFD-0 software was validated performing simulations in laboratory and hospital by Barbosa and Brum (2018), where the results were compared with commercial codes and experimental results.

2. THE CLEAN AIR ENCLOSURE SYSTEM

The Clean Air Enclosure System is divided into the Clean Air Enclosure, Atmosphere Conditioning System, Autonomous Refrigeration Unit and Data Acquisition and Control system. The Clean Air Enclosure is a chamber composed by stainless steel and polycarbonate, insulated the inner part of the external environment. The Clean Air Enclosure have a airlock to not expound the main chamber to the environment and sliding gloves, as presented in Fig.1. The Atmosphere Conditioning system is responsible to clean the air inside the chamber, using a duct system, one fan, HEPA filters, providing the cleanliness level required and change the atmosphere characteristics. The Autonomous Refrigeration Unit is responsible to control the temperature and humidity performing different conditions to the future experiments. The Data Acquisition and Control system capture the information about what happens inside the chamber and present a feedback about the sensors installed in the equipment, showing the pressure, temperature and humidity. (Guerrieri and Nunes, 2019)

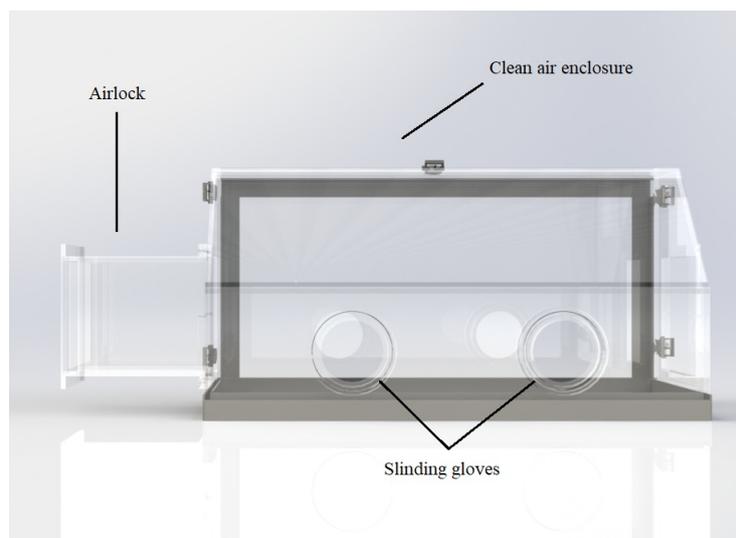


Figure 1. Drawing of the main chamber of the clean air enclosure with its main details.

The air clean enclosure is placed over a bench, and the air handling system is placed under the bench, optimizing the space in the lab. The air handling system is being developed to generate different pressures and work with different gases inside the chamber, besides controlling the humidity, temperature, and cleanness. The air handling system was separated into two parts, one to clean and to conditioning the atmosphere, and another to refrigerate. The clean air enclosure system has a data acquisition and control system, placed next to the workplace. The control system is composed of sensors, computers, and power supply. The air enclosure system will be controlled by LabView software saving the data provided by sensors (Guerrieri and Nunes, 2019).

This paper is focused on analyzing the airflow behavior and the contamination distribution at the chamber. The simulations performed with CONTAM 3.2/CFD-0 will provide important features to define the COTS (commercial off-the-shelf) equipment and components which will be used to assemble the final design of the clean air enclosure system.

3. NUMERICAL SIMULATION

The CONTAM 3.2 works with a sketchpad where the user can draw a schematic representation of a building. In the sketchpad, the user can determine the zone properties (floor area, contaminants concentration, temperature, and pressure), draw ducts, controls, and insert a simple air handling system, a way to implement an air handling system without having to draw and define an entire duct system. The software display presents tools to draw (ducts, walls, controls, boxes), data settings (schedules, contaminants, species, filters, sources, airflow elements), simulations parameters, level settings (

create a level, edit level information), view and weather (Walton and Dols, 2013). The software uses the ideal gas law to perform the calculations. The calculations about the airflow are made based on the principle of mass conservation which is solved by different numerical methods.

The simulations with CONTAM were divided into four steps. The first step is destined to define the suitable airflow rate without a contaminant source according to the characteristics of the chamber and the concentration of the contaminant. The second step is destined to analyze the influence of the contaminants density in the contaminant concentration. The third step is destined to define the required airflow rate with the presence of contaminants sources. The fourth is destined to analyze the fluid dynamics and the contaminant dispersion with the CFD-0. The methodology is exposed through the flowchart presented in Fig.2.

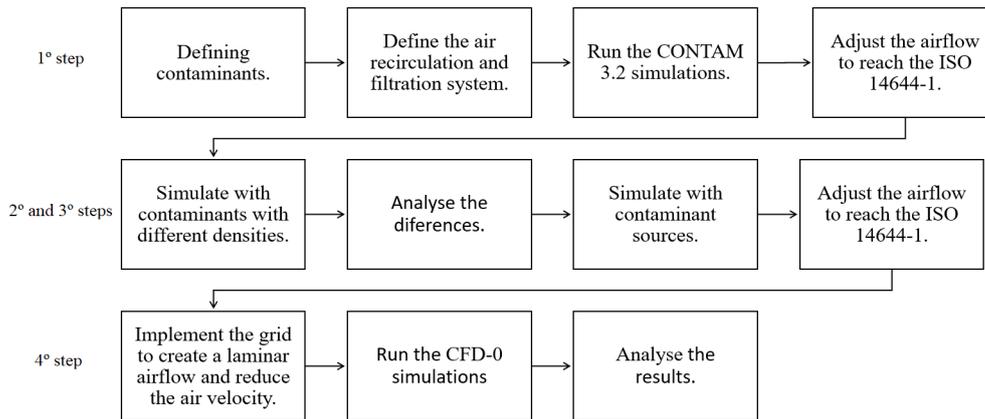


Figure 2. Flowchart exposing the methodology used to reach the results.

3.1 Airflow rate definition

In this first step, a sensitivity analysis is used to select the suitable airflow rate to clean the chamber (clean air enclosure) just considering the particles concentration. The ABNT (2019) was used to define the particle diameters distribution for the particle diameters range from $0,1 \mu\text{m}$ to $5 \mu\text{m}$. To check the cleanliness efficiency, the particle concentration was extrapolated to total particle concentration of $643 \mu\text{g}/\text{m}^3$. This concentration is higher than a reported maximum concentration, which is $261 \mu\text{g}/\text{m}^3$, in the INEA (2015) about the air qualities of the Rio de Janeiro state for place close to CEFET/RJ Campus Itaguaí. The density of the selected contaminant to define the airflow rate was the stainless steel density which is $7.95 \text{g}/\text{m}^3$, and the diffusion coefficient of $2 \times 10^{-5} \text{m}^2/\text{s}$.

The system modeling is composed of the zone (chamber), and the duct system equipped with a constant volume flow rate fan, an inlet terminal, an outlet terminal, and an external air intake, as see in Fig. 3. The clean air enclosure system is designed to use COTS parts. The choose filtering part was the HEPA filter featured in ABNT (2013) as ISO 40Hd with presents an efficiency of 99,9 % for all particle diameters. Different air flow rate was set to analyze the needed time to meet the Class 100 (ISO5) requirement of ABNT (2019) standard. It was simulated 6 different cases, changing only the airflow rate. All the settings used for Airflow rate definition is presented in Tab.2.

Table 2. Used CONTAM 3.2 settings for airflow rate sensitivity analysis.

Item	Value
Floor area	0.72 m^2
Level height	0.6 m
Duct length	1 m
Duct diameter	1 in
Duct shape	circle
Filter efficiency	99.9%
Airflow rate	1, 10, 20, 30, 40, and $50 \text{ m}^3/\text{h}$
Terminal free face area	0.055 m^2
Particle diameters	0.1, 0.15, 0.22, 0.33, 0.5, 0.75, 1.13, 1.7, 2.56, 3.84, and $5.76 \mu\text{m}$

3.2 Densities of contaminants

In this second step, new simulations are carried out to understand the influence of the contaminant density in the concentration decay. The simulations characteristics are the same as presented in the first step, changing only the contaminant densities for each material, and using just one airflow rate value which was 50 m³/h. Typical material particles for the desired usage of the clean air enclosure such as stainless steel, polycarbonate, aluminum, copper, silicon, glass, and PDMS were used in the simulations by setting the particle density.

3.3 Contaminants sources

The CONTAM 3.2 provides different models to characterize sources of contaminants like constant-coefficient, pressure-driven, cutoff concentration, decaying source, boundary layer diffusion, burst source, deposition velocity sink, and deposition rate sink. This work uses the constant-coefficient model which is characterized by the equation

$$S\alpha(t) = G\alpha - R\alpha \times C\alpha(t) \quad (1)$$

where $S\alpha$ is the contaminant alpha "source strength", $G\alpha$ the generation coefficient, $R\alpha$ the removal coefficient, $C\alpha$ the contaminant concentration, and t the time.

In this third step, eleven different particle sources related to each particle diameter of contaminants were created to simulate a manufacturing process. It was considered a source of one particle per second for each particle diameter. Then, it is analyzed their effects on the cleanliness level. It was used the same simulation setting presented in Tab. 2, performing a new sensitive analysis of the airflow rate in order to meet the Class 100 (ISO5) requirements.

Figure 3 shows the CONTAM 3.2 sketchpad with the sources and duct system. The simulations with the particle sources shows the influence of the contaminant diameter in the contaminant decay. All the contaminants generate rate are defined aiming to extrapolate the reality, oversizing the capacity of the system to clean the air and keep the contaminants concentrations below the Class 100 (ISO5) requirements ABNT (2019).

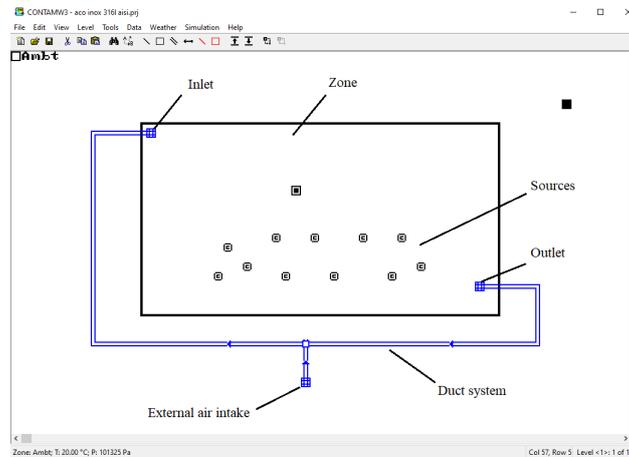


Figure 3. CONTAM 3.2 sketchpad with the duct system (in blue) and contaminant sources (black dots inside the zone)

3.4 CFD-0 simulations

After the CONTAM 3.2 simulations, the CONTAM/CFD-0 simulations are made to evaluate the airflow inside the chamber, checking the velocity of the air and the flow type. The simulations use a rectangular mesh, the power law interpolation scheme, standard air properties, k- ϵ turbulence model for simulations considering a 125m³/h airflow. To validate the CFD results, it was performed a sensitivity analysis of the four different number of meshes with rectangular elements. The convergence analysis was done comparing the air velocity in a centerline from the chamber back to the chamber front. The number of meshes were 251×125×125 (3,921,875 elements), 225×113×113 (2,873,025 elements), 201×101×101 (2,050,401 elements) and 151×75×75 (849,375 elements).

In this four step, the CFD-0 simulations were carried out to understand the airflow behavior during the operation of the chamber, and the contaminant dispersion. Because of a limitation of the software, the clean air enclosure was modeled as a rectangular design, different from the real design, see Fig. 1. A grid was implemented in the chamber domain to distribute homogeneously the airflow inside the chamber, reducing the possible high air velocity. The used settings in CFD-0 simulations are presented in Tab. 3. Figure 4 show the structure with the grid prepared in the CFD-0. The contaminant dispersion was also analyzed by setting the particle diameters of 0.1 μ m, 0.5 μ m, 1.13 μ m and 5.76 μ m, and the produced particle frequency of one particle per second.

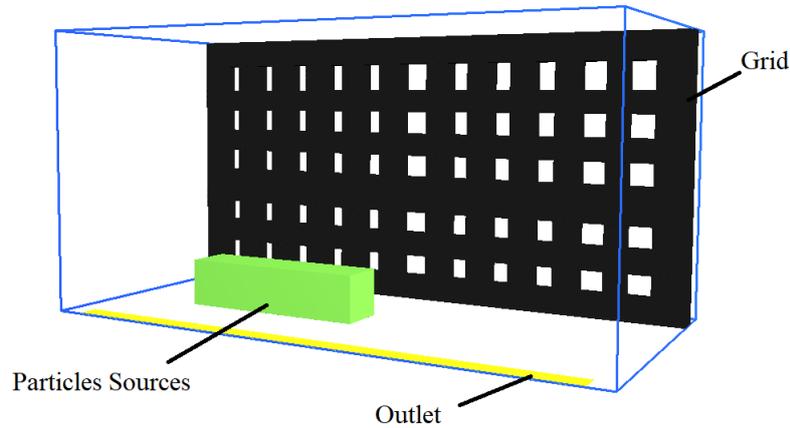


Figure 4. The chamber domain used to simulate through the CFD-0 software.

Table 3. Settings of the CFD-0 simulations.

Item	Value
Control volumes (Mesh)	3375000
Fan input area	0.055 m ²
Output area	0.055 m ²
Density of the air	1.1774 kg/m ³
Reference temperature	20 °C
Convective scheme	Power law
Turbulence models	Laminar and k-ε
Particle sources dimensions(meters)	0.4 × 0.1 × 0.2

4. RESULTS

4.1 Defining characteristics

Table 4 shows the needed time and the mean velocity at the chamber inlet according to the airflow rate to achieve the Class100 (ISO5) requirements. For the proposal of this work, the airflow rates lower than 20 m³/h do not provide a cleaning suitable time, meaning it would take a while to be able to use properly the clean air enclosure. Figure 5 presents the particle concentration decay along the time. Looking at the air velocity, the suitable value will depend on how sensitive is the performed application in the chamber.

Table 4. Airflow, Time and Velocity.

Air flow (m ³ /h)	Time (minutes)	Velocity of the air in the inlet(m/s)
1	> 60	5.05 × 10 ⁻³
10	38	5.05 × 10 ⁻²
20	16	1.01 × 10 ⁻¹
30	11	1.52 × 10 ⁻¹
40	8	2.02 × 10 ⁻¹
50	7	2.53 × 10 ⁻¹

4.2 Particles with different densities

The realized simulations for different particle densities provide similar times of cleanliness. Particles with lower densities demand a bit more time to be removed. This difference is neglected for this work proposal because it does not influence significantly the final results.

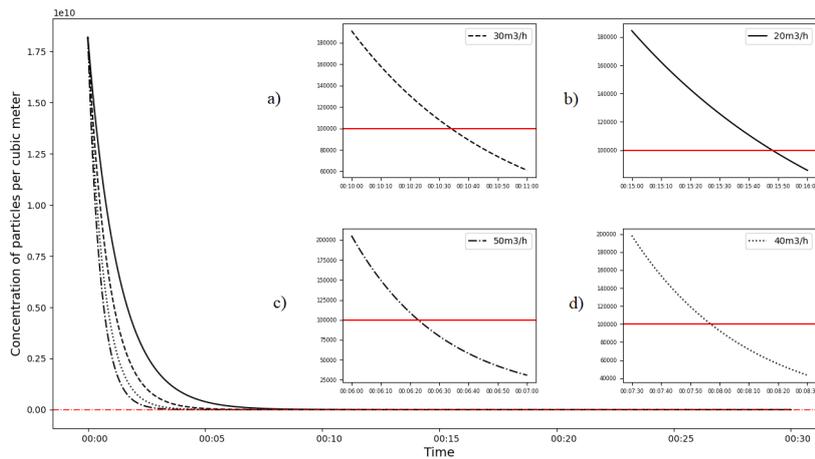


Figure 5. Comparison between cleaning efficiency of airflow rates. a) The cleaning efficiency of 30 m³/h. b) The cleaning efficiency of 20 m³/h. c) The cleaning efficiency of 50 m³/h. d) The cleaning efficiency of 40 m³/h.

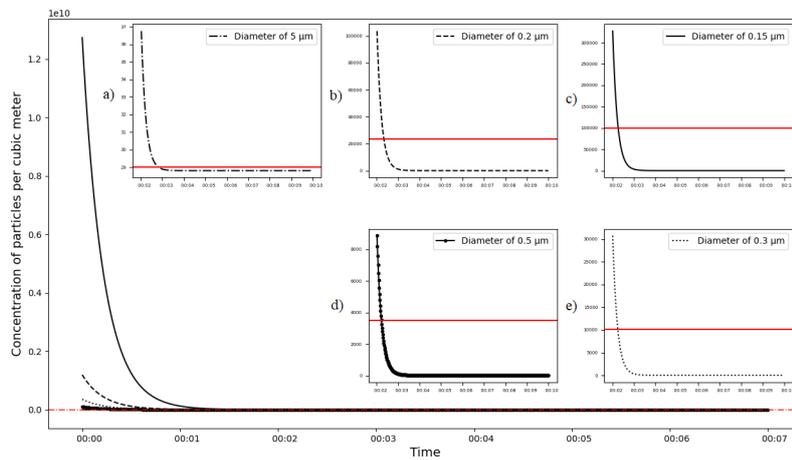


Figure 6. Particle concentration decay for different particle diameters. a) Particle concentration decay with 5 µm diameter. b) Particle concentration decay with 0.2 µm. c) Particle concentration decay with 0.15 µm. d) Particle concentration decay with 0.5 µm. e) Particle concentration decay with 0.3 µm.

4.3 Concentration with particle sources

The presented results in the previous sections do not consider particle sources, just the cleanliness of the natural environment. The needed airflow rate to keep the Class 100 (ISO5) requirements must be different considering particle sources. Considering the airflow rate of 125 m³/h, the Class 100 (ISO5) requirements is meet after 2.5 minutes. Due to the high velocity of about 1.11 m/s at the chamber, it was implemented a grid to reduce and homogenize the air velocity.

Figure 6 shows the needed time to clean the different particle diameters in order to meet the Class 100 (ISO5) requirements. The concentration of particles per cubit meter of a 5 µm particle diameter stabilizes in 28, however, the concentration limit for this diameter according to the Class 100 (ISO5) requirements is 29. It shows the airflow rate of 125 m³/h is suitable, however, to reduce the concentration one option is to increase the airflow rate. The other particle diameters stabilizes the concentration in a much lower value compared to the Class 100 (ISO5) requirements.

4.4 CFD-0 analysis

Figure 7 presents the meshes sensitive analysis results. The air velocity in a centerline from the chamber back to the chamber front was used to compare the results concerning the number of meshes. The simulations with the meshes number of 2,873,025 was used due to its low computational cost and low results difference. The chosen mesh demands one-third of the time to be solved than the most refined mesh.

The simulations with CFD-0 tool shows the airflow behavior, allowing to evaluate the existence of recirculation in some part of the chamber and to see the generated contaminant distribution by the contaminant sources. The simulations

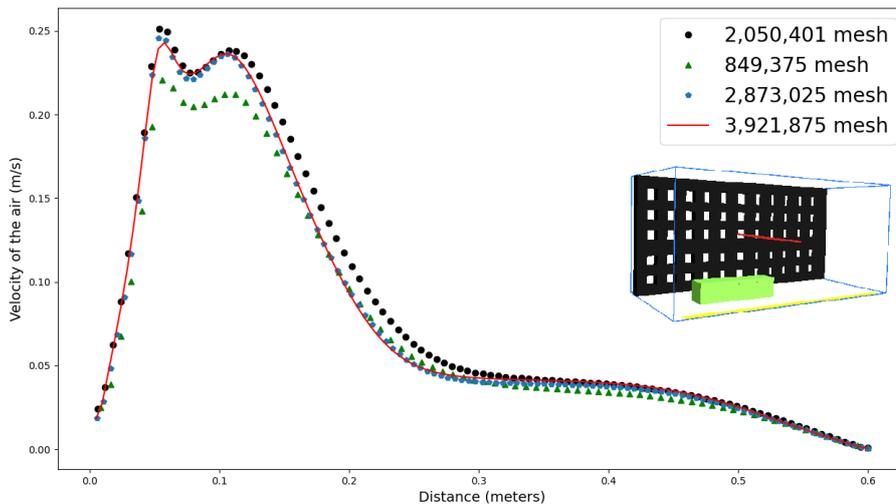


Figure 7. Comparison between different meshes in relation of the air velocity in a centerline from the chamber back to the chamber front (red line in the miniature figure).

show airflow behavior through the grid satisfactory with small turbulence flow close to the grid holes and laminar flow for other parts of the chamber. Figure 8 shows the streamlines at the chamber cross-sectional area for different positions.

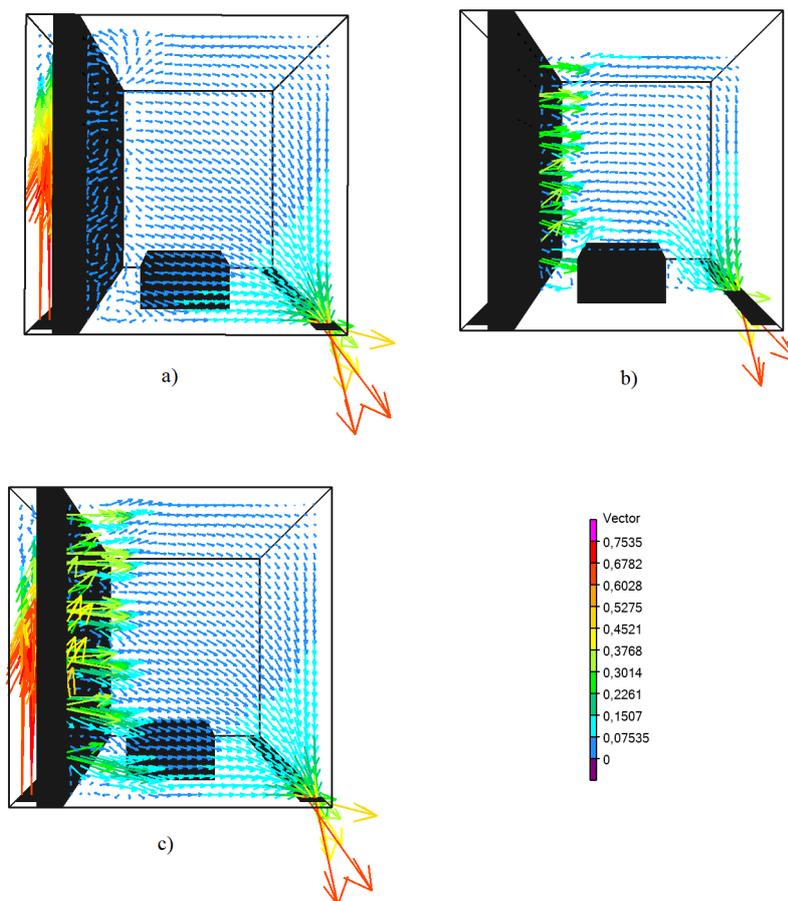


Figure 8. Streamlines showing the airflow behavior inside the chamber in different positions, values in [m/s].

The presented concentration results is given by kg of contaminant per kg of air, and it is not the exactly same as the simulations by CONTAM. Figure 9 shows different views of the contaminant dispersion at the chamber. As it was

expected the high concentration is kept close to the particles source, and the particles are dragged through the outlet.

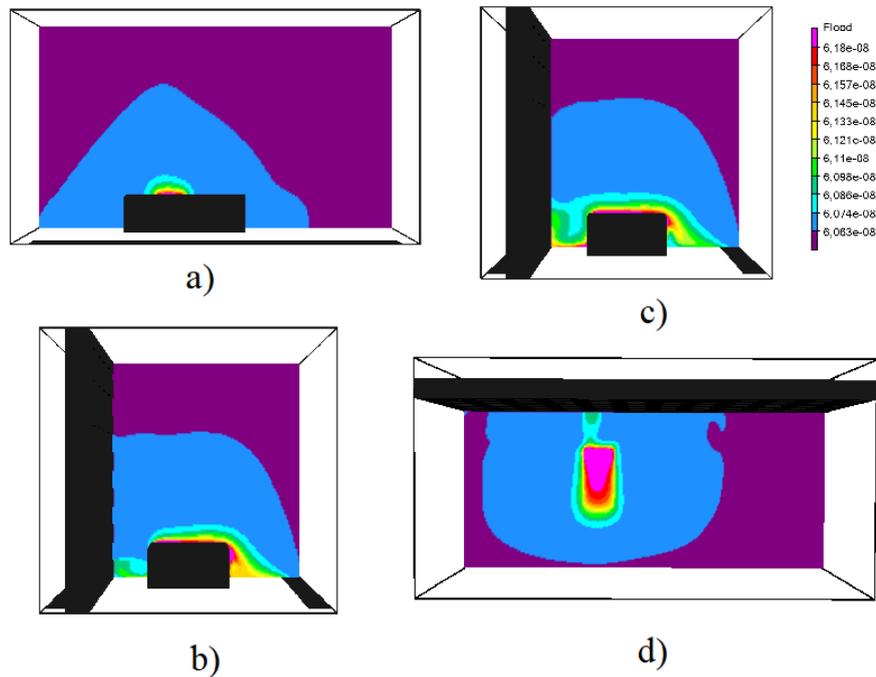


Figure 9. Generated contaminant dispersion by the particle source which emits the $5,76 \mu\text{m}$ diameter particles, in kg of contaminant per kg of air. a) The contaminants dispersion visualized by the frontal view of the chamber. b) the contaminant dispersion visualized by the side view aligned to the grid holes. c) The contaminant dispersion visualized by the side view aligned to the grid bars. d) The contaminants dispersion visualized by the top view of the chamber.

5. CONCLUSION

This work focused on defining an optimum cleaning system to act in the clean air enclosure system. The suitable airflow rate to reach the Class 100 (ISO5) is $50 \text{ m}^3/\text{h}$ with no particles source and $125 \text{ m}^3/\text{h}$ with particle sources. It was observed an issue to clean particles bigger than $5 \mu\text{m}$, which demands a higher airflow rate to keep the environment under the Class 100 (ISO5). The defined airflow rate is easily found in COTS equipment, fulfilling the goal of the project, providing the demanded cleanliness level at a low cost.

The simulations showed an acceptable airflow behavior (air velocity distribution) and contaminant dispersion for this proposal work. A future work to optimize the grid is needed to evaluate the influence of different diameters and positioning.

6. ACKNOWLEDGEMENTS

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