Interface Phenomena for a Multifunctional Air-Water Micro-Particle Collecting and Filtering System

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Abstract: The confinement clean rooms used in industry are susceptible to higher count of particles per cubic meter of air after the usual work program. To decrease the economic and technological effects of particle concentration a micro-cleaning device was elaborated. A first approach of a 3D model of the device was produced and different issues were found. Using COMSOL Multiphysics to identify new model connections and process data, several design choices have been made and tested to produce a better device. The newest device shape provides better handling of the surrounding air flow and a longer autonomous operating time.

Keywords: filter, water, air, clean room

1. Introduction

A new device concept of a multifunctional particulate collector was designed to meet the very strict regulations of clean room and medical-biological controlled environment. The device is meant to assist the existing installations on achieving better performance or to offer an alternative to costly equipment or servicing.

2. Model requirements

2.1 Clean room

There are three types of clean rooms in use worldwide: confinement clean rooms, working area clean rooms and biological security clean rooms. Each of them has to meet a set of requirements in order to make the clean room working properly.

The concept device was designed around a confinement clean room (Fig.1, 2) which has a particle count over 1000 parts per cubic meter on a vertical airflow. This particular clean room is used for isolating sensitive parts of machinery from the dangers posed by floating particulate in the air. Definitely, the major contaminant in a clean room is the human operator [1] and in this case, with a vertical air flow, the floor has a higher concentration of particles than any other surface, thus the device should clean the floor in a manner that does not affect the good working order of the clean room.

The average particle size that is encountered in the clean room is 0.3 µm – 2.5 µm and the materials include biological matter, mineral dust, pieces of rubber insulation from cables and flakes of metal from improper surfaces.

Table 1 : Clean Room Parameters

Parameters	Value
Type of air flow	Vertical turbulent
Construction materials	Concrete with epoxy sealed floor and pvc coated walls
Work schedule	1-2 hours per day max
Inside temperature	Thermostat controlled 21 °C ± 1°C
Filters	HEPA 12/13
Air pressure	Atmospheric pressure +50 Pa
Average air speed	0.5m/s
Area	150 m^2

2.2 Proposed concept

Due to the special requirements and conditions inside the clean room a new concept was elaborated (Fig. 1). The device will use a water filtration strategy to trap debris picked up by an air stream beneath the body. The top section consist of a thin dynamic water layer which carries particles that fall under gravity or air flow to the same collection tank. A pump moves water through a reverse osmosis filter to avoid having particulate material being re-exposed to clean room air.

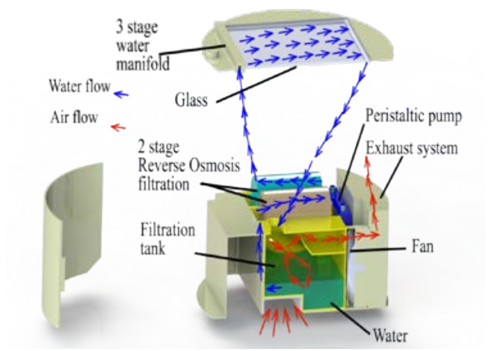

Figure 1: Exploded view of concept device μC3

After drafting and visualizing the device concept with 3D modeling software, several concerns emerged:
1. Where should be placed the device as to maximize its particle collection rate?
2. What impact will have the design and material structure of the device on the air flow?
3. How can be minimized the effect of exhaust air flow?
4. What happens at the interfaces throughout the device?

3. Use of COMSOL Multiphysics

3.1 Device area of action

To analyze where the maximum collection rate will be, a COMSOL simulation was built depicting the flow of air the clean room. Several assumptions about the conditions were made including but not limited to laminar vertical flow and floor evacuating of air, in order to streamline calculation time and complexity of model. The simulations were run in time dependent mode to provide a better understanding of air dynamics involved. Figure 2a shows that the flow of air adhere to walls and has a zone of disturbance where it meets the desk. That is the area where the work will be done by human operators, thus it will be also the most likely area of particle concentration. In fig 2b the velocity field shows the same distribution. In this case, because the air is evacuated through the floor of the clean room [1] the vectors depicting air speed tend to converge under the desk. In a normal, non-floor ventilated clean room, the interface between desk and floor will be a hotspot for particle collection.

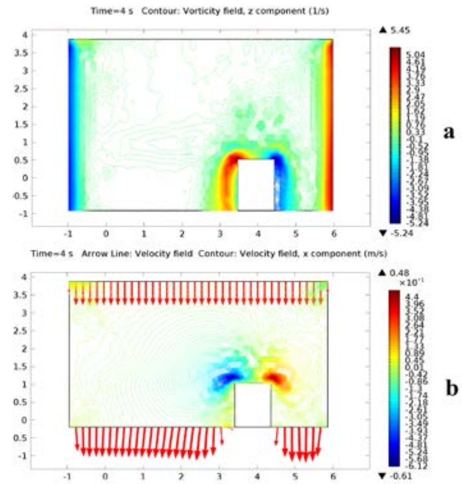

Figure 2: a) Vorticity field in clean room;
b) Velocity field in clean room

3.2 Device structure impact

To correctly appreciate the impact of the device shape and size on surrounding air flow, the previous simulation was reworked. An approximation of the device's shape, with scale dimensions was introduced next to the desk Figure 3. The same conditions and assumptions were kept into the next iteration. Introducing a device, lower on the floor, the same pattern of flow emerges, indicating a disturbance zone. Since the study was done in a 2D model was assumed that a much greater disturbance in the laminar flow emerges due the interactions between room air flow, inlet air flow and exhaust air flow (Figure 1).

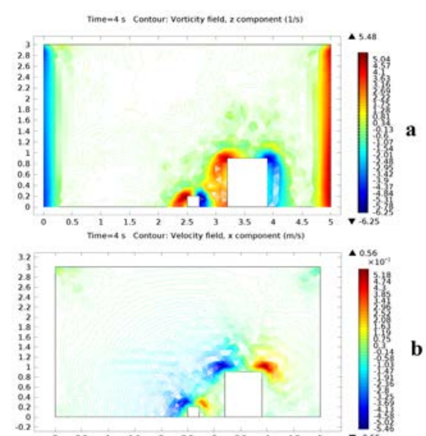

Figure 3: a) Vorticity field in clean room, b) Velocity field in clean room

On the top of the device there is a thin water film which is meant to act as a particle capture and transportation environment. The model considers direct and laminar air flow over this water film. To create a more suitable air flow around the device, the suction system has to be sized as to absorb larger quantities of air. That is advantageous because a larger volume of the removed air from under the device will carry on a greater number of particles collected from the floor.

3.3 Exhaust air system design

Removing a large quantity of air from under the device creates two problems: the battery size and power and the exhaust air velocity and volume.

The battery problem is easily mitigated with large volume air fans and efficient motors plus additional (optional) charging stations.

The exhaust air problem is interesting from an engineering stand point, because of the limited volume inside the device (Figure 4).

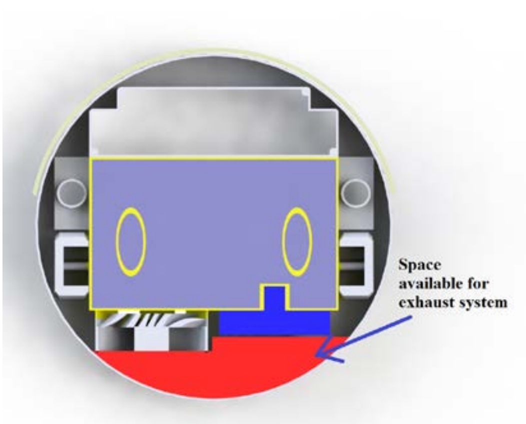

Figure 4: Space available for exhaust air system

From the outline depicted above a vector image was obtained and inserted in COMSOL Multiphysics as a domain of study.

Approximate values of *inlet air* and *outlet air* were calculated and data introduced into the simulation (Eq. 1, 2). Air speed was computed at two time interval, 0s and 60s to allow stabilization of flow (Figure 5).

The values for airspeed at outlet were high, (over 1.5m/s) so a redesign of the enclosure was tested. It added two baffles to provide a longer path and a speed reduction. This new design was analyzed in the same conditions as before (Figure 6). The air speed at outlet dropped to 0.5m/s, slower than the air speed in the clean room.

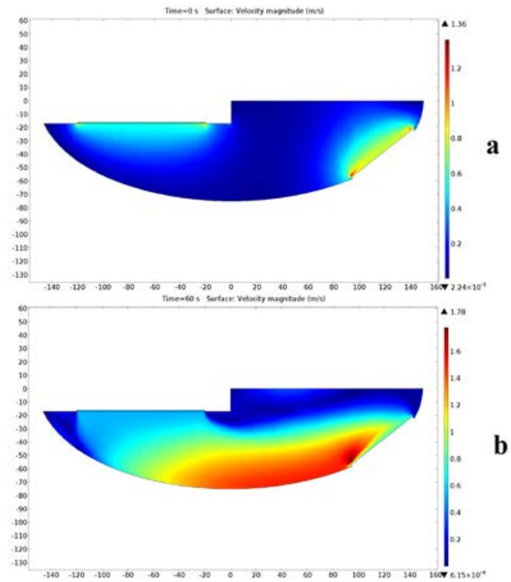

Figure 5: a) Initial air speed, b) Air speed after 60s

Between the exit of the fan and the inlet of the exhaust system a HEPA filter was adapted. The filtration action further reduced airspeeds and made for a safer device, retaining carbon dust and small particles.

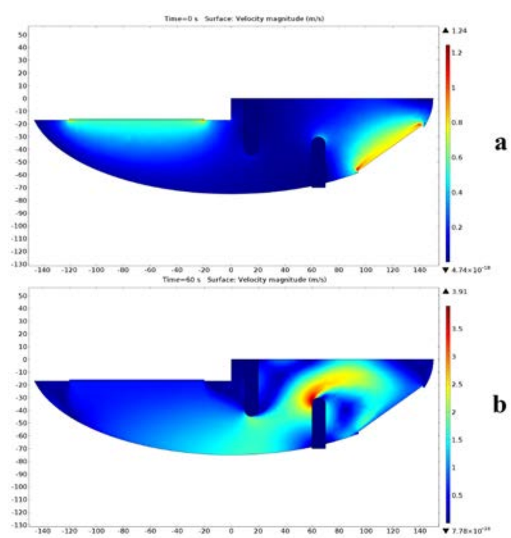

Figure 6: a) Initial air speed with baffles, b) Air speed after 60s with baffles

3.4 Air - water interface

Air - water surface is the most important interface in the device system. It is crossed by particles collected by the device during operation cycle. The particles have to traverse this interface and to remain trapped in water.

This device uses a thin water film moving across a TiO_2 plate surface aiming to capture airborne particles that are present in suspension. This water film, due to the interactions with the oxide layer has an electric charge exclusion zone for micro particles. [2] In this case the particles come in contact with the water from the air-water surface above and are carried away by the water flow into the tank (Figure 7).

Because the substrate is a hydrophobic surface, this cleaning method can be used in two ways. One, where the water flows constantly and traps particles from above, and another one where the water flow washes the surface at regular intervals allowing a buildup of particles on the surface [3].

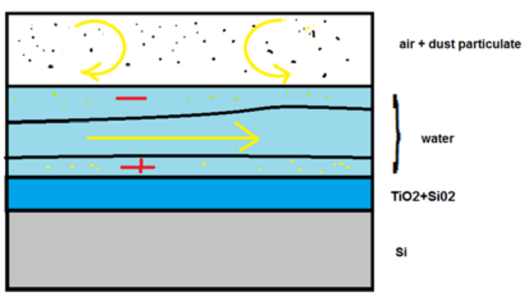

Figure 7: Schematic cross section of water layer on top of a hydrophobic TiO_2 layer.

The movement of captured particles was simulated in COMSOL (Figure 8) using particle tracking module.

$$\frac{\partial}{\partial t}(\rho \boldsymbol{u}) + \nabla \cdot (\rho \boldsymbol{u} \otimes \boldsymbol{u} + p\boldsymbol{I}) = \nabla \cdot \tau + \rho g \quad (1)$$

Cauchy moment equation

$$\frac{\partial p}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0 \quad (2)$$

Navier-Stokes mass continuity equation

The equations that control particle movement are Brownian force:

$$F = \zeta \sqrt{\frac{12\pi k_B \mu T r_p}{\Delta t}} \quad (3)$$

and fluid particle interaction

$$F_v = -\sum_{j=1}^{N_t} n \boldsymbol{F_D} \delta(\boldsymbol{r} - \boldsymbol{q_j}) \quad (4)$$

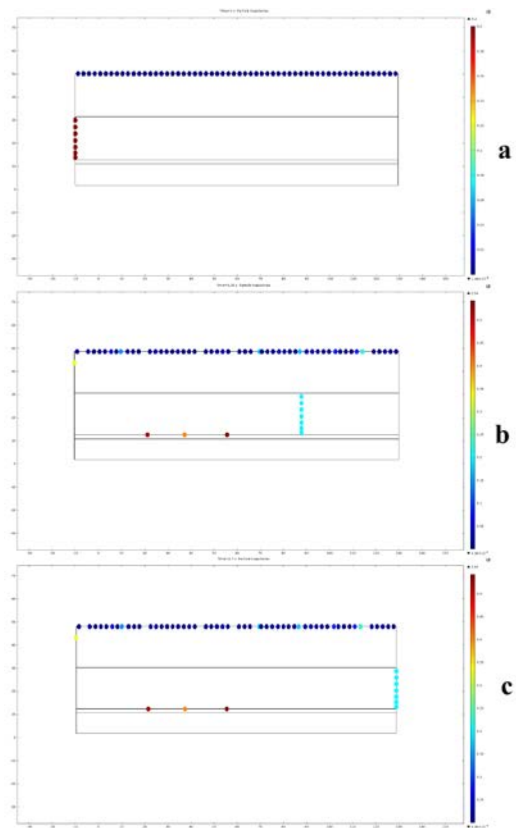

Figure 8: Particle tracking simulation per time: a) 0s; b) 0.35s; c) 0.7s

4. Results

In a confinement clean room there are many use-cases (Fig. 9) for a device that collect all kinds of particles in an automated way. The design of the device allows for operation without interfering with existent clean room system or operators. Better design practices and utilization of space inside the device can minimize unwanted disturbances around the structure and make it even more efficient by allowing better airflow for airborne particle capturing. The air water interface when crossed by particles in the target size is allowing efficient capture of particles and a greater volume of water is beneficial to increasing time of operation.

5. Conclusion

By careful designing a better performing device can be obtained (Figure 9, 10). Changing around the placement of the water tank and batteries, the two biggest space occupiers, a more slick body is possible.

Figure 9: Clean room [4] with model-simulation of redesigned device concept (μC3)

The new concept has a redesigned air water manifold that allows a greater area of particle transfer.

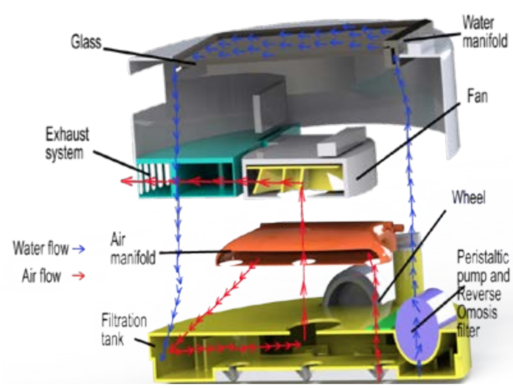

Figure 10: Redesigned μC3 concept model

The larger water tank sits lower and is capable of collecting a larger amount of debris before needing to be cleaned.

The power fan was changed to a turbo blower and the new exhaust system and HEPA filter keep emission of particles and disturbances low.

7. References

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