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Personnel Safety Performance Enhancement of a Numerically Modeled Biological Safety Cabinet Class II Type A2 By Adding an Air Curtain

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Abstract— Biological safety cabinets (BSC) are devices that are widely used by microbiologists and pharmacists when handling biohazardous materials. A safe working environment shall be achieved while using such devices. However, the safety of the BSC operators is compromised as these devices are very sensitive to the air pattern surrounding them. Isolating the interior area of the BSC from the surroundings using an air curtain at the front of the BSC was simulated using a 3D numerical model. The air used as an air curtain was drawn from the breathing zone of the operator to decrease the probability of any contaminant escape from the inside of the device towards the face of the operator. This numerical study was done simulating the dimensions, air velocities, air pressures of an actual 4-foot BSC class II type A2. The air curtain modification was added to the numerical model to compare the safety performance enhancement before and after adding the air curtain. To calculate the performance enhancement in the numerical study 1x10^5 particles were discharged from the supply HEPA filter and were traced at the breathing zone of the operator where the BSC after modification showed 16.32 % decrease in the number of the traced particles

Index Terms— Air curtain, biological safety cabinet, contaminant escape, numerical study, particle tracing, personnel safety, performance enhancement,

1 INTRODUCTION

Biological safety cabinets class II type A2 is the most widely used type among all other BSC types. This device should provide personnel, product, and environmental protection. Studies shows that product and personnel protection are not always achieved when using the BSC.

BARBARA W. RAKE, 1978 [1], Tested a BSC class II type A to detect the effect of cross drafts on the safety of the BSC's users and on the safety of the products they use. BARBARA concluded that cross drafts above 90 fpm compromises the protection provided by the BSC for the users given that drafts from windows and open doors can exceed 200 fpm also the air velocity from air conditioning diffusers can range between 300 fpm & 750 fpm

Janet M. Machert Achert and Melvin EW. First, 1984 [2] performed two studies on a BSC class II type B1. The first study was to detect the effect of personnel movement, air inflow velocity, sash opening size, activity pace and operator's hand location on the contamination escaping the BSC. The second study was performed to detect the effect of gender, height, weight, and skill degree on the rate of contaminant escape outside of the BSC they found out that even properly operated BSC lose some portion of aerosolized particles. The researchers concluded that testing the BSC during normal operation activities provides different results than the static testing of these devices. They pointed out that further dynamic tests should be performed to evaluate the cabinet design.

Robert L. Jones Jr. and David G. Stuart, 1990 [3] done a research to detect the effect of varying the inflow air velocity and the supply air velocity on the performance of the BSC class II by testing 17 BSC devices of 3 different models. 5 BSCs of model I, 5 BSCs of model II and 7 BSCs of model III. The researchers developed a relation between the supply velocity and the inflow air velocity and concluded that optimization between theses velocities should be considered otherwise product and personnel protection will be compromised

Ellen Jo Baron, J. Michael Miller, 2007 [4] made a survey detecting the probability of infection transmission to laboratory workers in 88 facilities including, hospitals, laboratories, and academic institutions. Researchers deduced that microbiologists are more vulnerable to acquire infections than other personnel. they also pointed out that 29 facilities (33%) out of the 88 facilities in the survey reported at least 1case exposed to infection

Rong Fung Huang and Chun I. Chou, 2009 [5] performed a study on a modified BSC class II type B2 adding an air jet curtain at the front of the BSC and deduced the jet effect on the product & the personnel safety provided by the BSC. They concluded that as the HEPA filtered air velocity increases the pressure inside the cabinet will also increase resulting in a straight air curtain where the jet air impinges on the doorsill and escape from the BSC subjecting operators to contamination. Increasing the suction velocity of the air inside the BSC will create low pressure inside the cabinet which is lower than the ambient pressure generating a severely concave air curtain which induces vortex inside the BSC subjecting the product to contaminants also developing cross contamination inside the cabinet. Fine-tuning of the HEPA filtered air velocity and the suction air velocity will

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result in a slightly concave curtain which is the optimum configuration to obtain negligible inward contamination dispersion, outward contamination escape, and cross contamination inside the BSC.

Rong F. Huang and Chun I. Chou, 2009 [6] performed another study to deduce the dynamic influence on a BSC class II type B2 with a jet air curtain. They concluded that the slightly concave air curtain improved the personnel protection in both static and dynamic experiments performed on the BSC, the straight air curtain had the lowest personnel protection performance of all curtain models while the BSC with no air curtain of had an accepted performance in the static tests, but generated severe leakage during the dynamic tests

Shih-Cheng Hu & Angus Shiue, 2015 [7] done a research on a BSC class II type A2 to detect the effect of the air flow quantity on the particle count inside of the BSC using 3 different operating apparatus with different heights ranging from 10 cm to 30 cm. The researchers concluded that as the air flow quantity increases inside the BSC the particle count decreases. also, the particle count decreases as the height of the apparatus increase

Thomas Hinrichs and Sven Gragert, 2016 [8] performed an experiment on two BSC class II type A1 devices from different producers to demonstrate the airflow perturbation induced by BSC user activities. Researchers concluded that each operator activity induced different air flow disturbance than the other. Hence the minimum safe down flow and inflow velocities are also different for each activity. The researchers demonstrated that the BSC producers are directed to decrease the energy consumption of the BSC by decreasing the device's airflow jeopardizing the safe use of the BSC

Bruno Perazzo Pedroso Barbosa and Nisio de Carvalho Lobo Brum, 2017 [9] performed a numerical study using CFD on a BSC class II type A2 to assess the sensitivity of the BSC towards the down flow velocity, contamination generation rate, inflow velocity, air change rate inside the room, thermal load inside the room, and to detect the time required for contaminants to escape outside of the BSC and reach the breathing zone of the operator. The time required for all the contaminant particles to reach the operator's breathing zone was 60 minutes. The researchers concluded that the BSC's contaminant spreading depends mainly on the room 's air flow pattern, the air inflow velocity and room 's level of turbulence.

Kara F. Held, Robert Thibeault,2019 [10] performed a study on two BSCs class II type A2 of different sizes 4-foot, 6 feet respectively. They experimented the effect of using different heat sources inside the BSC on the personnel, product & environmental protection of the BSC. They used 4 different heat sources to perform this experiment. Researchers deduced that it's not safe to work with heat sources inside the BSC as contamination can escape to the operator or to the product

Xavier Alcaraz, Nick Filipp, 2019 [11] compared the performance of several BSCs class II type A2 and BSCs class II type B2 handling vapor fraction of chemotherapy drugs experimenting a small spillage and a large spillage of chemicals inside the BSC. Traced chemicals outside of the BSC were not detectable for both types; hence the risk of inhalation of volatile hazardous materials is low outside of the BSC. Meanwhile volatile material inhalation risk inside the BSC is probable. The researchers pointed out that operators should not insert their faces inside the BSC for cleaning purposes in case of hazardous materials spillage inside the BSC.

2. NUMERICAL METHOD

This research was performed to study two numerical models using COMSOL Multiphysics 5.3a as follows: Case A: a numerical model of a commercial BSC without any modification

Case B: a numerical model of the BSC after modification

2.1. Physical model

2 models were built as shown in Fig 1, Fig 2 for case A and case B where a BSC with width of 1200 mm, height of 1250 mm and depth of 800 mm was modeled also an area in front of the BSC was added resembling the interface between the operator and the cabinet.

The sash opening of the BSC was simulated as a rectangle with width of 1200 mm and height of 250 mm. The BSC had two internal suction slots of width =1200 mm and depth=100 mm, one of these slots was positioned 100 mm behind the sash opening while the other slot was 100 mm in front of the rear wall of the BSC. An Interior fan was modeled as a rectangle with width of 200 mm and height of 150 mm. Two cylinders with diameters of 100 mm each and length of 500 mm were added simulating the BSC operator's hands where 300 mm of the cylinder's total length was inside of the device and the remaining length was extruded outside of the device. The cylinders were 300 mm apart from each other. Case B is a modified version of case A where the only difference between them is the fan module in front of the device

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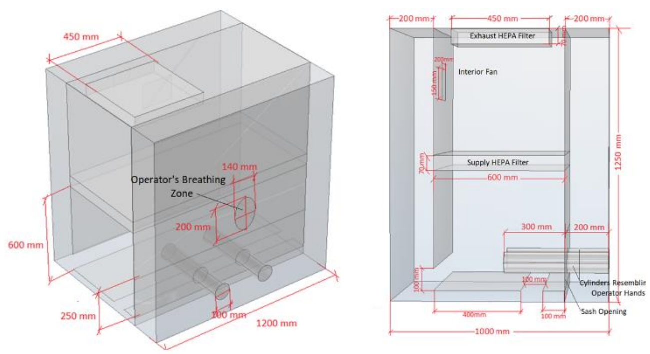

Fig 1, Case A BSC numerical model isometric view and side view

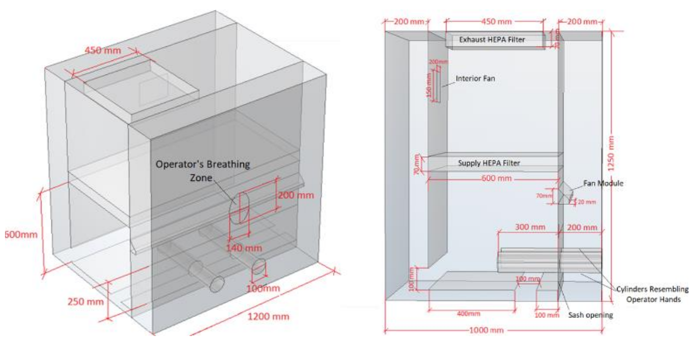

Fig 2, Case B BSC numerical model isometric view and side view

2.2. Numerical Study

Two different solution studies were used to solve each numerical model as follows:

Study 1

A stationary study was used to solve the turbulent flow physics that was used to simulate the air flow outside and inside of the BSC and the free and porous media flow physics which was used to simulate the air moving through the HEPA filters as shown in Fig 3

Study 2

The NSF/ANSI 49 [12] states that for personnel protection test 1x10^8 to 8x10^8 spores of bacteria should be released from a nebulizer inside the BSC with a velocity of 0.5 m/s over a

period of 5 mins where slit samplers and impingers outside of the cabinet are operated for 30 minutes to sample the escaping viable spores outside of the BSC. For the numerical study a time dependent study was used to solve the particle tracing for fluid flow physics in all the domains where 1x10^5 particles were released from the supply HEPA filter face with a velocity of 0.5 m/s over a period of 5 minutes and the total sampling time was 6 minutes for simplification

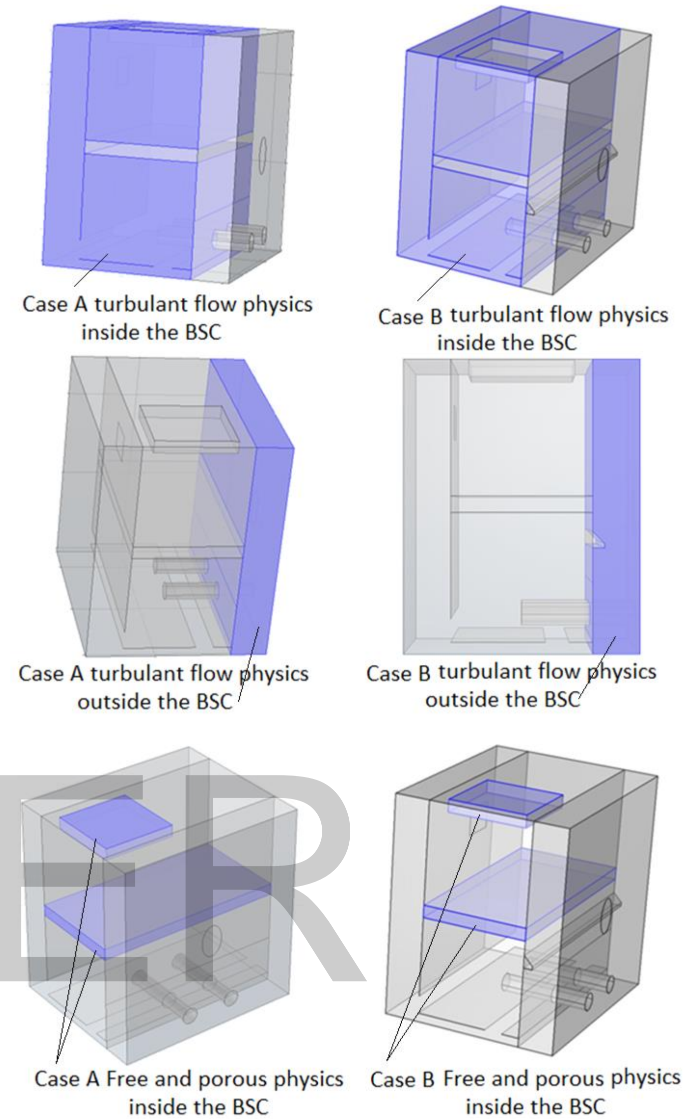

Fig 3, Different physics used for solving case A and case B study 1

2.3. Boundary Condition

The main boundary conditions that were used during the study for case A and case B are shown in Fig 4 and Fig 5 respectively.

for Case A, the air moves from the room air inlet boundary into the sash opening inlet boundary where it's drawn by the interior fan along with the air from the supply HEPA filter outlet boundary. The air exits the interior fan boundary then it splits into two air streams the first air stream flows into the exhaust HEPA filter inlet while the other air stream flows through the supply HEPA
filter inlet boundary

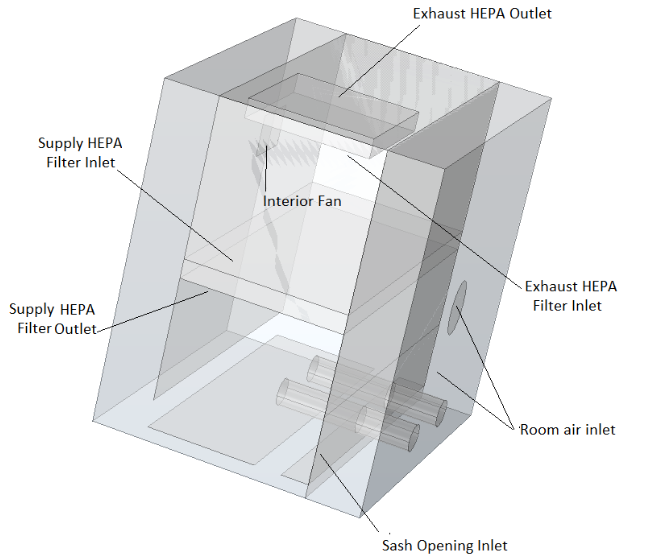

Fig 4, Case A BSC Main boundary conditions

for Case B, the air moves from the room air inlet boundary into the fan module inlet boundary where it's accelerated and then exits from the fan module outlet boundary into the sash opening inlet boundary where it's drawn by the interior fan along with the air from the supply HEPA filter outlet boundary. The air exits the interior fan boundary then it splits into two air streams the first air stream flows into the exhaust HEPA filter inlet while the other air stream enters the supply HEPA filter inlet boundary

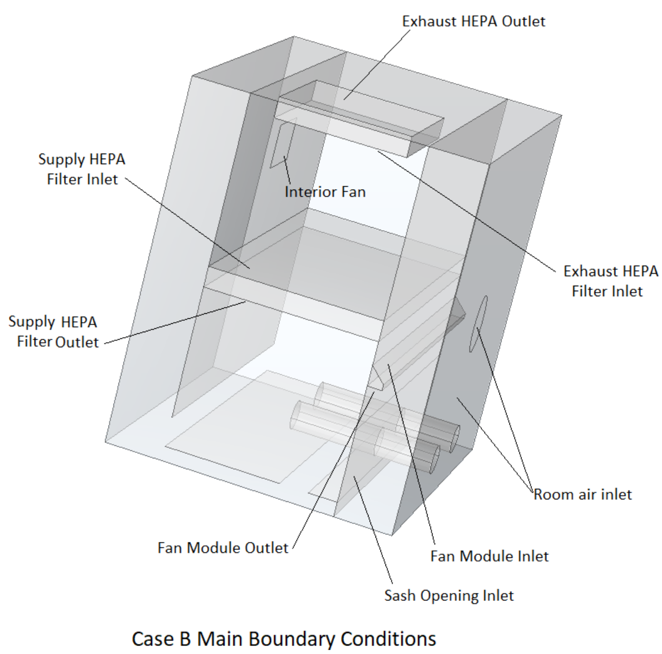

Fig 5, Case B BSC Main boundary conditions

The boundary condition parameters identified for the main boundary conditions are given in Table 1

Table 1 Main boundary condition parameters for case A and case B BSCs

Turbulent flow physics inside the BSC			
Boundary condition	**Parameter**	**Case A**	**Case B**
Sash opening inlet	Inlet Pressure	0 Pa	0 Pa
Supply HEPA filter outlet	Normal inflow velocity	0.5 m/s	0.5 m/s
Supply HEPA filter inlet	Normal outflow velocity	0.5 m/s	0.5 m/s
Exhaust HEPA filter inlet	Normal outflow velocity	0.5 m/s	0.5 m/s
Interior fan	Static pressure	500 Pa	500 Pa
Turbulent flow physics outside of the BSC			
Room air inlet	Mass flow rate	0.12182 kg/s	0.12182 kg/s
Fan module inlet	Normal outflow velocity	NA	0.10182 m/s
Fan module exit	Mass flow rate	NA	0.12182 kg/s
Sash opening inlet	Outlet Pressure	0 Pa	0 Pa
Free and porous media flow physics inside the BSC			
Supply HEPA filter inlet	Normal inflow velocity	0.5 m/s	0.5 m/s
Exhaust HEPA filter inlet	Normal inflow velocity	0.5 m/s	0.5 m/s
Supply HEPA filter outlet	Outlet Pressure	0 Pa	0 Pa
Exhaust HEPA filter outlet	Outlet Pressure	0 Pa	0 Pa

2.4 MESHING

Meshing is an Important step in any numerical analysis as the precision of the results depends on the size of the used mesh. The element sizes used for the domain meshes were fine with maximum element size equals to 0.0581 m while fine and finer meshes were used for the boundaries with maximum element sizes equals to 0.0581 m and 0.0405 m, respectively. The remaining geometry was meshed using a free tetrahedral mesh also refinement of the corner meshes was performed at the edges of the geometry.

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3. RESULTS AND DISCUSSION

The results of the numerical studies were calculated for both BSCs (case A and case B). Both cases had identical HEPA filter's air velocities of 0.5 m/s and identical inflow air velocities of 0.375 m/s. The only difference was that case B BSC had a fan module providing an air curtain with an air velocity of 1.68 m/s.

3.1 Mass Balance

To validate the numerical solution, mass continuity was investigated for all inlet and outlet boundary conditions as shown in Table 2.

Table 2 Mass balance for main boundary condition for case A and case B

Turbulent flow physics inside of the BSC mass balance							
Source Boundary condition			Destination Boundary condition			Error percentage	
Boundary title	Mass flow rate (Kg/s)		Boundary title	Mass flow rate (Kg/s)		Case A	Case B
	Case A	Case B		Case A	Case B		
Sash opening inlet	0.12 182	0.12 182	Exhaust HEPA filter inlet	0.12 182	0.12 182	0%	0%
Supply HEPA filter inlet	0.43 315	0.43 315	Supply HEPA filter outlet	0.43 315	0.43 315	0%	0%
Interior fan	0.55 497	0.55 497	(Exhaust HEPA filter inlet) + (Supply HEPA filter inlet)	0.55 497	0.55 497	0%	0%
Turbulent flow physics outside of the BSC mass balance							
Room air inlet	0.12 182	NA	Sash opening inlet	0.12 182	NA	0%	0%
Room air inlet	NA	0.12 182	Fan module inlet	NA	0.12 182	0%	0%
Fan module exit	NA	0.12 182	Sash opening inlet	NA	0.12 149	0%	0.27 %
Free and porous media flow physics inside the BSC mass balance							
Supply HEPA filter inlet	0.42 078	0.42 078	Supply HEPA filter outlet	0.42 078	0.42 078	0%	0%
Exhaust HEPA filter inlet	0.11 739	0.11 739	Exhaust HEPA filter outlet	0.11 739	0.11 739	0%	0%

3.2 Velocity & Pressure Plots

Velocity and pressure plots were generated visualizing the behavior of the air across different physics as shown in Fig 6 and Fig 7

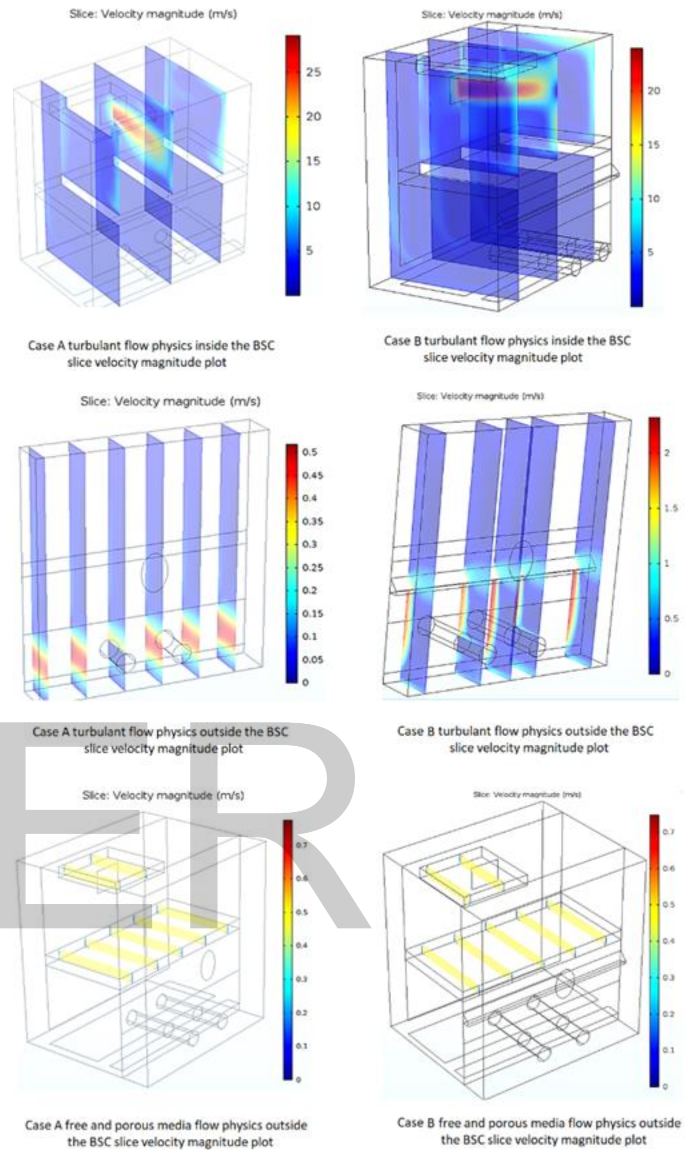

Fig 6, Slice velocity plot for case A and case B BSC

As shown in the previous figure the velocity distribution inside the BSC is identical for both modeled cases while the velocity distribution outside of the BSC is different due to adding the fan module where for case A the velocity plots shows that the air is drawn from the area facing the sash opening inlet while for case B the air is drawn from the breathing zone of the operator then it enters the fan module where it's accelerated in a downwards direction forming a high velocity air curtain isolating the inside of the BSC from the outside of the BSC

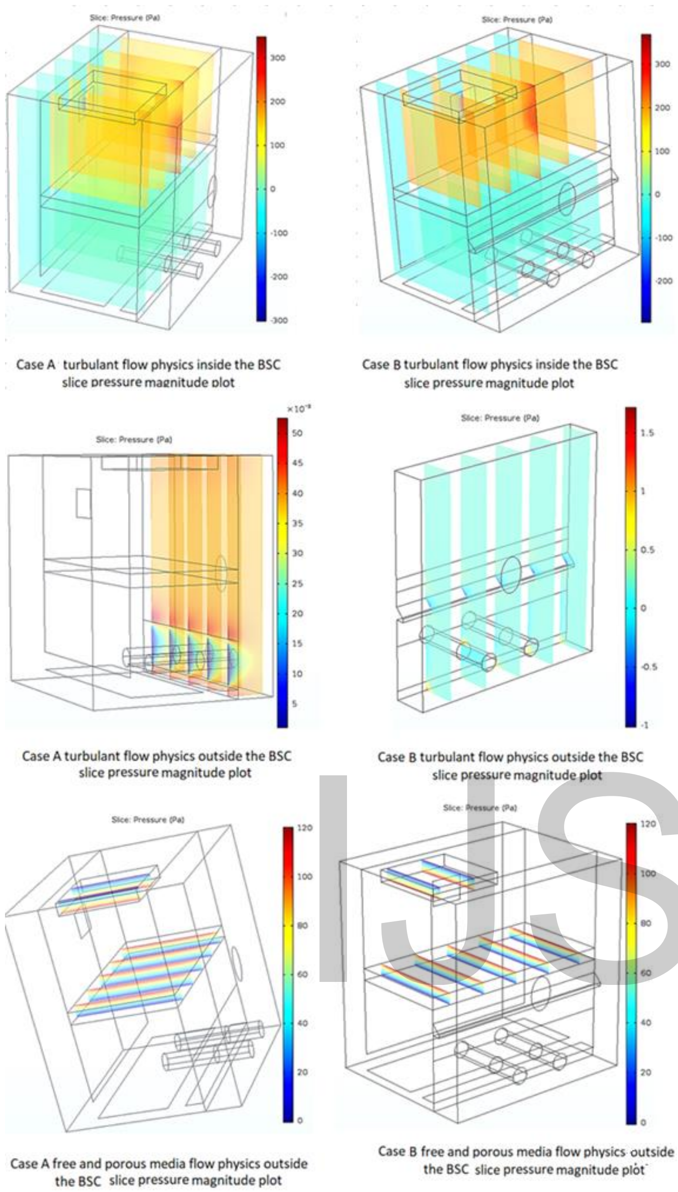

Fig 7, Slice pressure plot for case A and case B BSC

The pressure magnitude plot shown in Fig 7 is nearly identical to the pressure magnitude readings of the pressure gauge installed in the commercial BSC which was modeled by case A BSC where it had a gauge pressure drop through the HEPA filters of 120 Pa and a gauge pressure reading outside the BSC of 0 Pa

3.3 Particle count

Particles were discharged from the supply HEPA filter inlet boundary and were traced at the breathing zone of the operator and at the outside of the BSC as shown in Fig 8, Fig 9

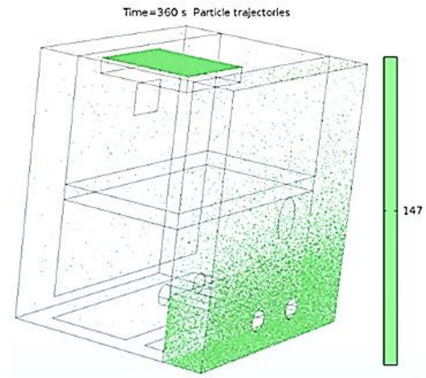

Fig 8 (a), Particle count at the breathing zone of the operator for case A BSC

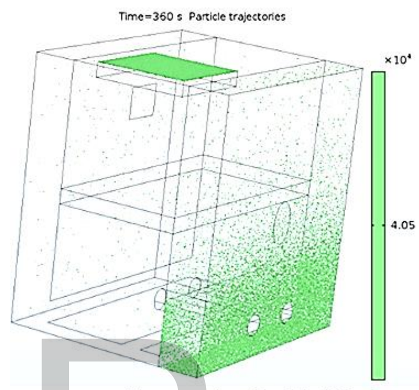

Fig 8 (b), Particle count outside the BSC at locations other than the breathing zone of the operator for case A BSC

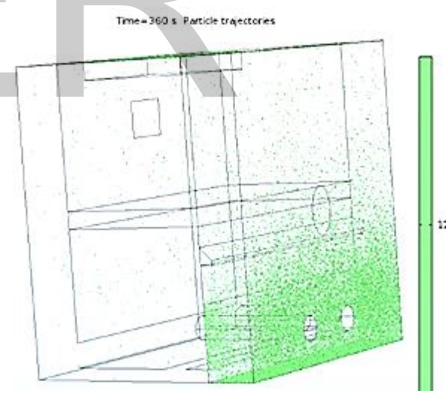

Fig 9 (a), Particle count outside the BSC at locations other than the breathing zone of the operator for case B BSC

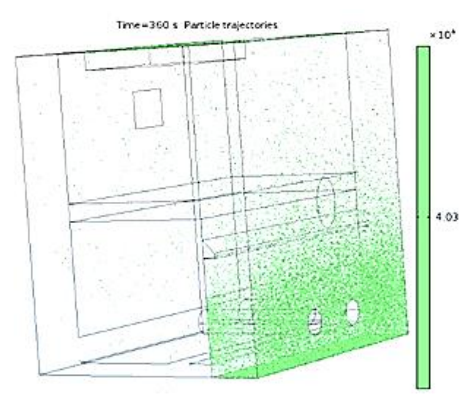

Fig 9 (b), Particle count outside the BSC at locations other than the breathing zone of the operator for case B BSC

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4. Conclusion

From the results of the two studied models the following points were concluded:

1. The mass flow rate at some of the common boundaries were not identical with a maximum deviation percentage of 3.6365%
2. Case A velocity plot shows that the air is drawn inside of the cabinet from the region in front of the sash opening inlet, where the air passes parallel to the two cylinders extruding from the device therefore even the air colliding with the cylinders is drawn inside of the cabinet. For case B, the velocity plot shows that the air from the fan module collides perpendicularly on the cylinders where the air flow splits and some of the air is drawn inside the cabinet while the rest flows outwards from the cabinet jeopardizing the personnel safety
3. The number of particles collected at the breathing zone of the operator outside of the BSC for case B (modified) model was less than the particles collected outside of the case A (base model) BSC by 16.32%
4. The total number of the particles that were traced at the outside of the BSC at locations other than the breathing zone for the case B (modified) BSC were less than the total number of particles traced for the case A (base model) BSC by 200 particles
5. The enhancement due to the modification is considered a good enhancement but still a lot of particles did escape from the BSC which endangers the personnel using the device. Hence personnel must use protective equipment and take caution while handling dangerous materials inside of the BSC

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