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Analysis of Preferential Flow at the Front Mesh Cartridge of the Gas Mask Filter: Cases in Malaysia Climate Environment

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ABSTRACT

A gas mask respirator is essential for human protection from the hazardous and toxic chemical environment. The gas mask filter should be regularly checked, and the filter must be changed abruptly based on the temporal exposure to the toxic environment. Furthermore, the filter is exposed to a highly humid climate, and the high gas concentration speeds up the expiry cycle of the gas mask filter. Thus, this study aims to investigate the preferential flow absorbed into the gas mask filter and predict the potential area that presents the dead zone. In this study, a three-dimensional model of the commercial gas mask filter was modeled using the computational aided design (CAD) software. Four different humidity ratios of 50%, 60%,70%, and 80% as well as Five different filter concentrations of 20ppm, 100ppm, 200ppm, 300ppm, and 1000 ppm were simulated. The computational fluid dynamic (CFD) method was governed by continuity and Navier-stokes equation to investigate the presence of the dead zone based on several flow parameters. The result showed that the effects of the pressure, velocity, temperature, humidity, and concentration on the gas mask filter were analyzed. The pressure drop is seen in the charcoal filter region which experiences high-velocity circulation. The highest effect on the pressure drop, humidity, and concentration was seen for the case V filter. The high humidity ratio with the pressure drop in the gas mask filter also decreases the efficiency of filter concentration even though the temperature is constant. The high humidity ratio in the mask filter will retain the heat inside the gas mask filter, thus reducing the life cycle of the filter.

1. Introduction

A respirator is a protective equipment for workers who are exposed to hazardous and toxic chemicals in the workplace. A toxic environment like gas and vapor pollutants is hazardous to the

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human respiratory system as well as interferes the human breathing [3,6]. Thus, the National Institute of Occupational Safety and Health (NIOSH) Malaysia has been concerned about toxic gas vapor exposure which might be affected directly the employee, especially in the oil and gas industries [5,23] The usage of the respirator equipped with the gas mask filter approval by DOSH SIRIM is compulsory regulation before the workers' exposure to the emission of gas and vapor pollutants from the chemical processing plant [9]. The gas mask filter consists of the activated carbon and organic filter being effective adsorbents for a variety of airborne pollutants [1,8,15].

However, the frequent absorption of the gas mask filter in the pollutant's environment and the exposure to the humid climate speed up the expiry date of the filter even though the expiry date set by the manufacturer is still valid [2]. This phenomenon has happened when the worker has slightly hard breathing after a couple of days of using this equipment. Furthermore, the large surface of the commercial gas mask filter caused a low absorption rate through the filter paper and activated carbon and also reduce the filter lifetime [13]. In order to improve the absorption rate of the filter and activated carbon, the filter design can be optimized. The optimization of the structure filter manages to extend the protection time and reduce the cost of the filter usage as well as reduce the employee risk in the hazardous area [18]. Thus, the aerodynamic characteristic based on the preferential flow entering the filter was investigated to identify the angle of improvement of the filter structure.

The aerodynamic study in the gas mask filter is important to understand the flow characteristics passing through the filter and activated carbon layer in order to identify the adsorption rate of the filter. The filter and the activated carbon presence as the porous media material allow the flow to pass through the filter layer [11,12]. However, the flow characteristics in the filter layer weren't presented in the experimental study. Thus, the numerical simulation is the best option for presenting the flow characteristics in the gas mask filter. The simulation has presented the flow behavior of the preferential flow in the porous media filter as well as predicted the area of the dead zone. The dead zone normally occurred in the region of high-pressure drop as well as insufficient adsorption rate [12,19]. However, several researchers had done the simulation on the gas mask canister [7,10,20,24]. They reported that the results were in good agreement with the recent study, which provided the idea of the optimization process of the gas mask filter. Thus, the study on the aerodynamic behavior of the porous media filter with the different gas concentrations and humidity manages to explain in more detail and finally will be the benchmarking in gas mask filter industries. With the rapid development of computer and numerical methods, it is possible to analyze the flow variables in porous media within a gas and vapor filter by examining the aerodynamic properties of the flow field using computational fluid dynamic (CFD) tools.

The aerodynamic gas mask filter research facilitates the manufacturer of the filter to be aware of the environmental issues such as the high humidity, temperature, and gas concentration exposure frequently in the humid climate country such as Malaysia [21]. In Malaysia, NIOSH Malaysia had developed the experimental equipment in quantifying the several issues that have been discussed. Hence, in this study, the computational fluid dynamic method was implemented to study the aerodynamic characteristics in the porous media filter in different percentages of humid rate, temperature variation as well different gas filter concentrations. The simulation can provide the prediction of flow characteristics based on the theoretical basis of different commercial gas mask filters. Finally, this study might be the milestone to establish the new gas mask filter which might increase the performance of the filter to sustain the environmental issues rather than the previous commercial filter.

2. Methodology

2.1 Geometry of Difference Gas Mask Filter

The geometrical modeling for the gas mask was developed using the commercial aided (CAD) software called SOLIDWORKS 2020 software. In this study, three different commercial gas mask filters are developed and simulated. A 3-dimensional model of the gas mask filter is illustrated in Figure 2.1. There are five (5) parts in the gas mask a) main body cartridge, b) filter sheet back, c) filter charcoal, d) filter sheet top, and e) mesh cartridge. A detailed overview of the sequential parts and assembly is demonstrated in Figure 2.2.

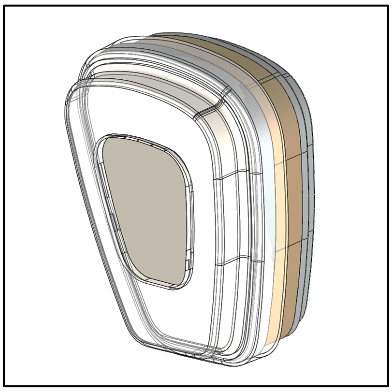

Fig. 1. The geometry of the gas mask model

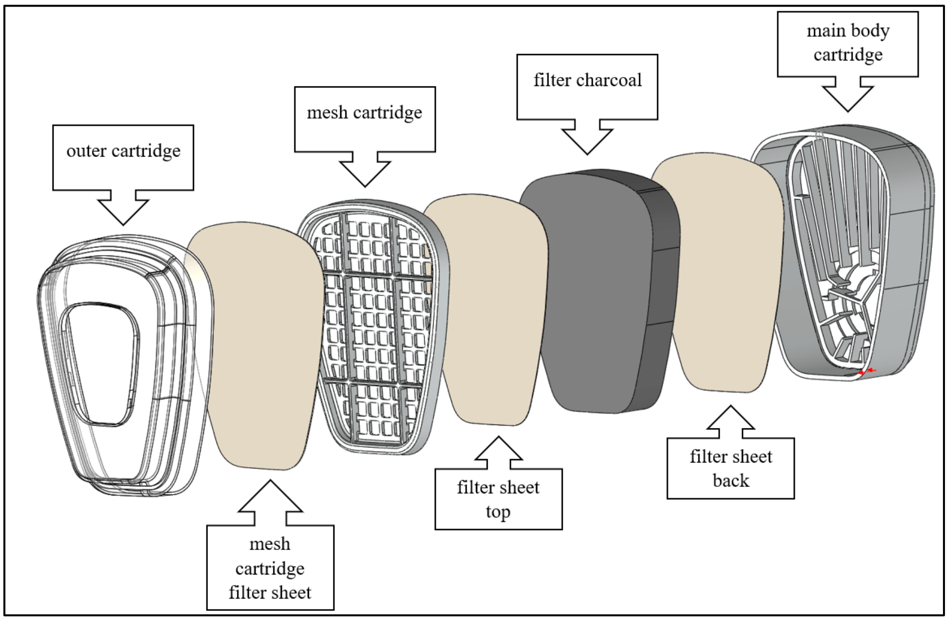

Fig. 2. The sequential part and assembly of the gas mask filter

2.3 Discretization Technique

ANSYS FLUENT 19.2 software (Canonsburg, PA, USA) is used for the simulation. This software manages to analyze multiple, automated parametric designs without complex programming. This software includes a variety of physical models that capture many types of phenomena related to fluid flow. The solver is based on the finite volume method with several types of arbitrary mesh topologies such as hexahedral, tetrahedral, wedge and pyramid elements. Additional mesh refinement is employed in specified porous media at the filter surfaces during calculation. The time derivatives are approximated with an implicit second-order accuracy in both space and time. This approach allows the use of larger time steps and provides better stability. Both velocity inlet and pressure outlet are computed to solve the continuity and Navier-Stokes equations. The physical law describing the problem of the gas mask is the conservation of mass, the conservation of momentum as stated;

$$\nabla . V = 0 \quad (1)$$

$$\rho \frac{DV}{Dt} = -\nabla P + \mu \nabla^2 V \quad (2)$$

Where is an air density, P is pressure, μ is the viscosity of air and V is an air velocity.

2.4 Meshing of the Gas Mask Model

Meshing of the gas mask model and details at the inlet and outlet is shown in figures 4 and 5.

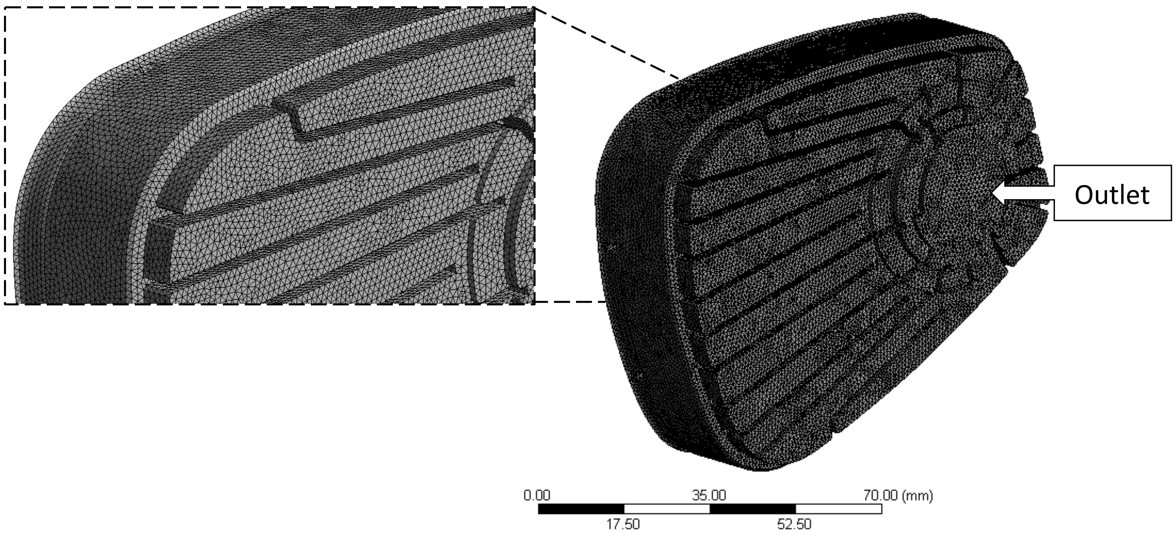

Fig. 4. Meshed model of the gas mask

2.5 Parameter Assumptions and Boundary Conditions

In this study, the fluid flow and heat transfer inside a filter was simulated. The flow is considered steady flow, incompressible flow, laminar flow at the filter layer, and turbulent as overall flow and no-slip condition. This filter is in contact with a natural heat source from the environment. The inlet air is approximately 1000 m^3/h for flow rate, the inlet temperature is 298.5K. In the inner space of the filter part of the model, water vapor is considered with various humidity (humidity: 50%, 60%, 70%, 80% based on Malaysia data) and is defined as a flowing fluid, and since the space for the mixed activated carbon is filtered, a porous medium model is used, which is made of a material called mixed carbon with a porosity coefficient of 0.85. The energy model is activated and the SST k-omega model with the use of standard wall function is exploited for fluid flow analysis. The concentration used for this condition is 20 ppm, 100ppm, 200ppm, 300ppm, and 1000 ppm.

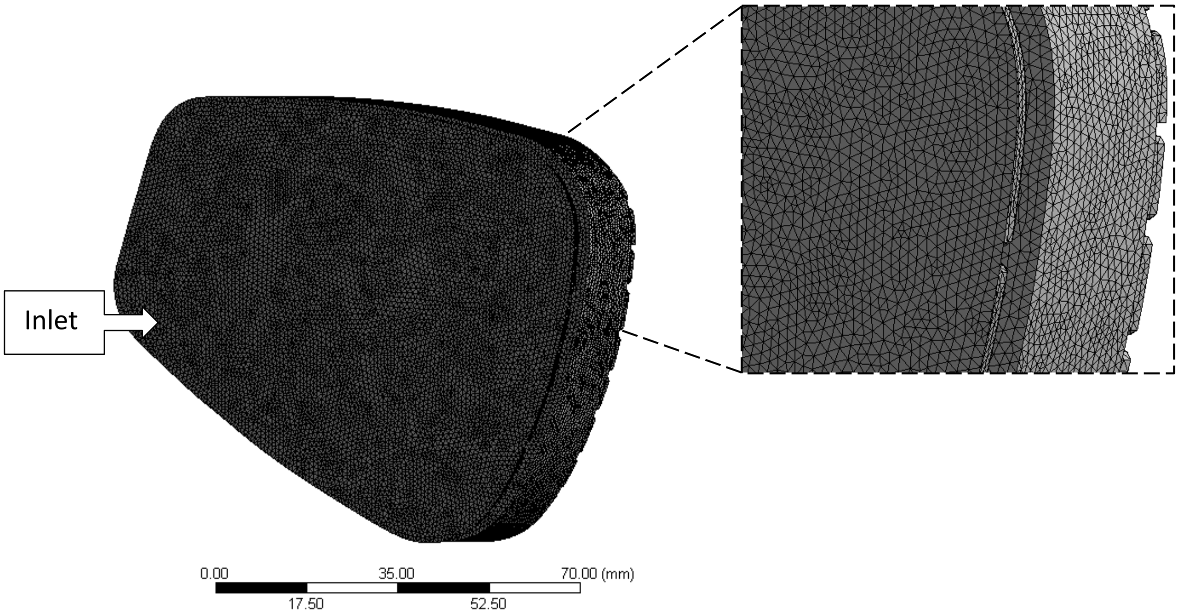

Fig. 5. The details Meshed model of the gas mask

Hence, the interface surface wall between the membrane and the airflow is a heat source with a value equal to +62122.815 Wm-3. Several different materials of filters are used; mixed activated carbon and fully activated carbon whose properties include density, specific heat capacity, thermal conductivity, and viscosity as stated in Table 1.

Table 1
Material properties

Material	Air
Density ($kg.m^{-3}$)	1.225
Specific heat ($j.kg^{-1}. K^{-1}$)	1006.43
Thermal conductivity ($W.m^{-1}. K^{-1}$)	0.0242
Viscosity ($kg.m^{-1}. s^{-1}$)	0.000017894

2.6 Porous Media Parameters

The simulation of the gas filter involves the porous media parameters in which the pressure drop in the gas filter normally comes from the filter paper and activated carbon. The Reynold number of 78,000 is used in this simulation. Both viscosity and inertial effect will be considered. Thus, the forcheimer equation is adopted to describe the momentum dissipation through the porous media as stated in the equation;

$$-\frac{\Delta P}{L} = \alpha \mu V_s + \beta \rho V_s^2 \quad (3)$$

Where α is the reciprocal permeability of the porous material or viscosity parameter. β is usually called the inertial parameter. ΔP is the pressure drop of the porous medium zone. L is the length of the flow direction; μ is the fluid viscosity. Vs denotes the superficial velocity of the fluid entering the porous medium zone. The filter paper and activated carbon used in the rfp-1000 gas filter are consistent with the references. Therefore, the coefficients of the filter layer and the activated carbon layer are consistent with the references. The coefficients for the filter layer and coefficients for the activated carbon layer are determined.

$$\alpha_1 = 2.19 \times \ 10^9 m^{-2}, \beta_1 = 7.5 \times 10^4 m^{-1} \quad (4)$$

The coefficients for the activated carbon layer are determined as

$$\alpha_2 = 2.19 \times \ 10^9 m^{-2}, \beta_2 = 7.5 \times 10^4 m^{-1}$$

3. Simulation results

3.1 Pressure Drop on the Gas Mask Filter Concentration under Local Humidity Condition

In this study, the effect of the pressure drop on the gas filter under the local humidity is illustrated in Figure 6. Figure 6 shows the pressure drop distribution at the gas mask filter for the different ratios of humidity and concentrations. From the observation, the pressure drop was slightly increased from the lower to the higher concentration of the gas mask filter. The pressure drop was also occupied more at the region of the left side of the charcoal filter as compared to the region of the right side. This is due to the flow streamline being re-circulated at the left region of the filter as well as loss in momentum and disrupting the radial flow and finally forming the dead zone. Furthermore, the highest-pressure drop was observed for case I of 80% humidity with 1000ppm of concentration. The pressure drop was also seen in the huge region of the charcoal filter as compared to the pressure at the surface boundary. This phenomenon was expected and agreed upon in studies by Su *et al.*, [20].

The pressure drop was seen to be slightly lower at the boundary surface of the filter. This phenomenon becomes worsens due to the presence of a humid climate and finally increases the pressure drop. The water vapor was also less dense than dry air even though simulated at the same temperature. Thus, the high humidity tends to decrease the density of air as well as lower its pressure.

3.2 Heat Propagation Effect under Different Concentrations and Ratios of Humidity

The increases in the water vapor ratio might be caused by the increases in the local temperature in the filter layer. This is due to the water vapor retaining the heat, especially in the charcoal filter as shown in Figure 7. However, the result has shown that not much difference in terms of temperature difference at the filter layer for different environments water ratio as well as concentration. This phenomenon occurred due to the porous medium effect on the charcoal filter which manage to distribute the temperature to the entire filter

From the figure, the average value of the temperature is occupied almost 70% of the region of the gas mask filter. Even though the temperature is almost similar, the efficiency of the filter concentration is experiencing decreases due to the high humidity in the local environment.

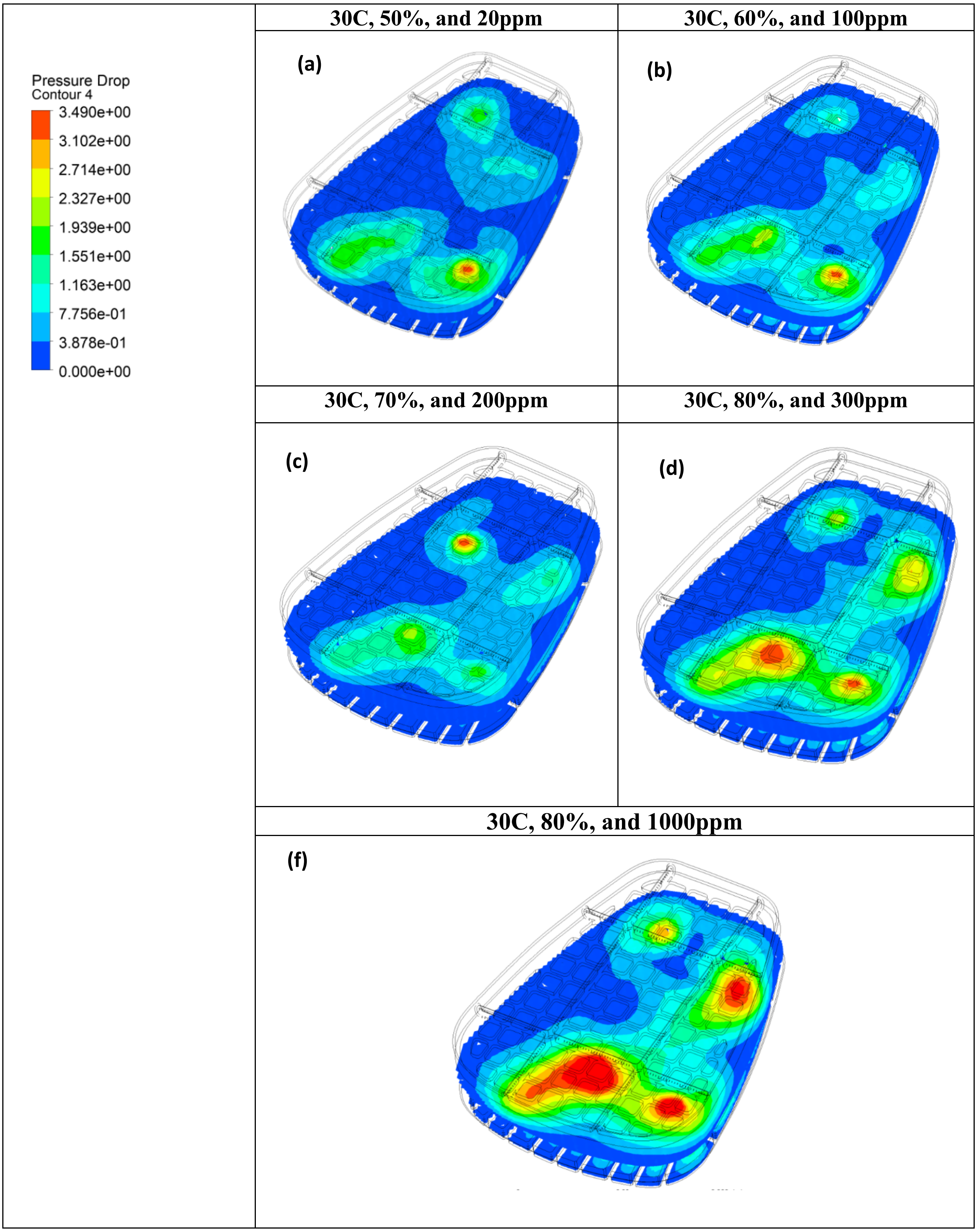

Fig. 6. Distribution of the pressure drop (a) Case I- Temperature at 30°C, the humidity of 50 %, and filter concentration of 20ppm (b) Case II- Temperature at 30the °C, the humidity of 60 %, and filter concentration of 100ppm (c), Case III- Temperature at 30°C, the humidity of 70 % and filter concentration of 200ppm (d) Case IV- Temperature at 30°C, the humidity of 80 % and filter concentration of 300ppm (e)) Case V- Temperature at 30°C, the humidity of 80 % and filter concentration of 1000ppm

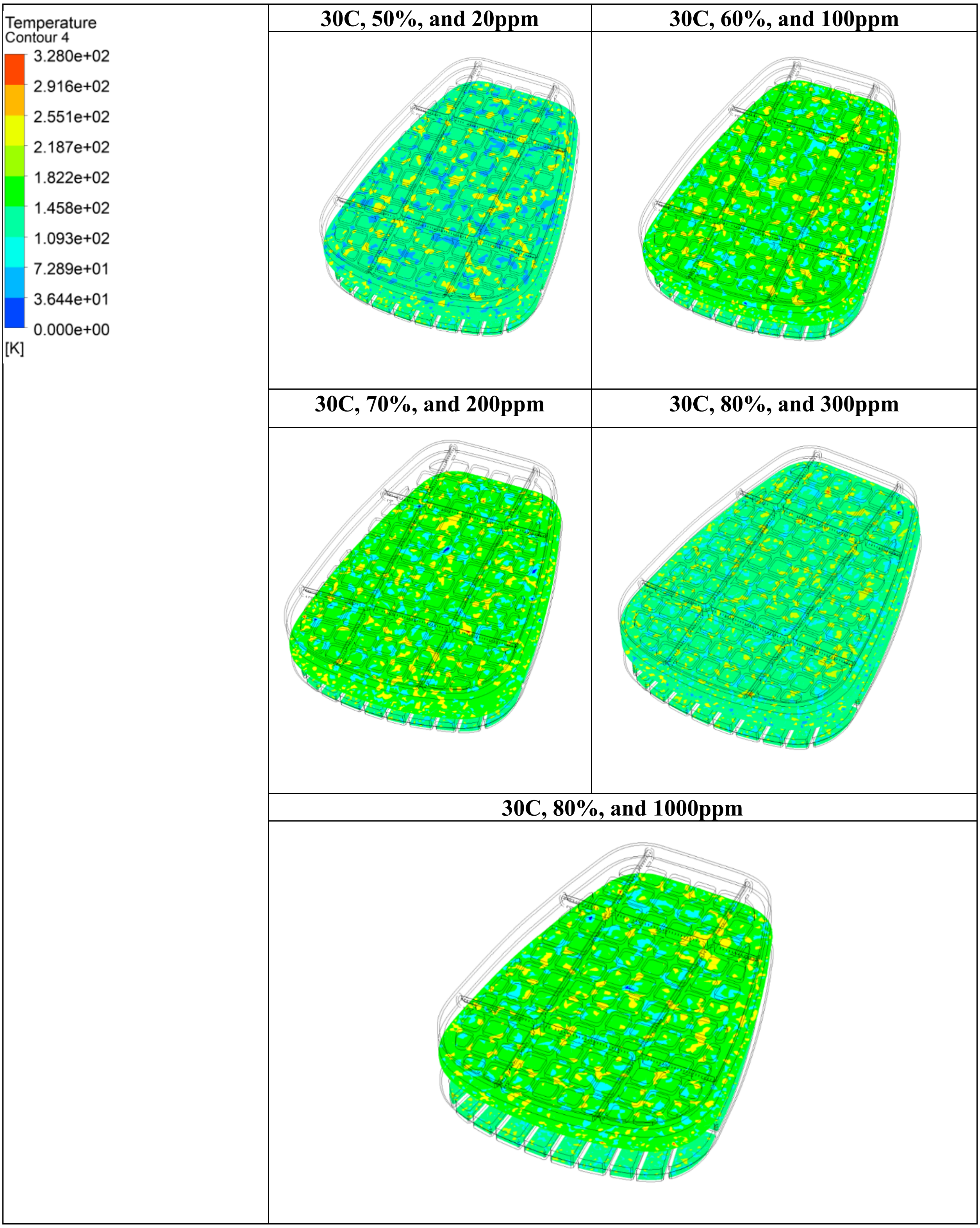

Fig. 7. Distribution of the temperature (a) Case I- Temperature at 30°C, the humidity of 50 %, and filter concentration of 20ppm (b) Case II- Temperature at 30°C, the humidity of 60 %, and filter concentration of 100ppm (c), Case III- Temperature at 30°C, the humidity of 70 % and filter concentration of 200ppm (d) Case IV- Temperature at 30°C, the humidity of 80 % and filter concentration of 300ppm (e)) Case V- Temperature at 30°C, the humidity of 80 % and filter concentration of 1000ppm

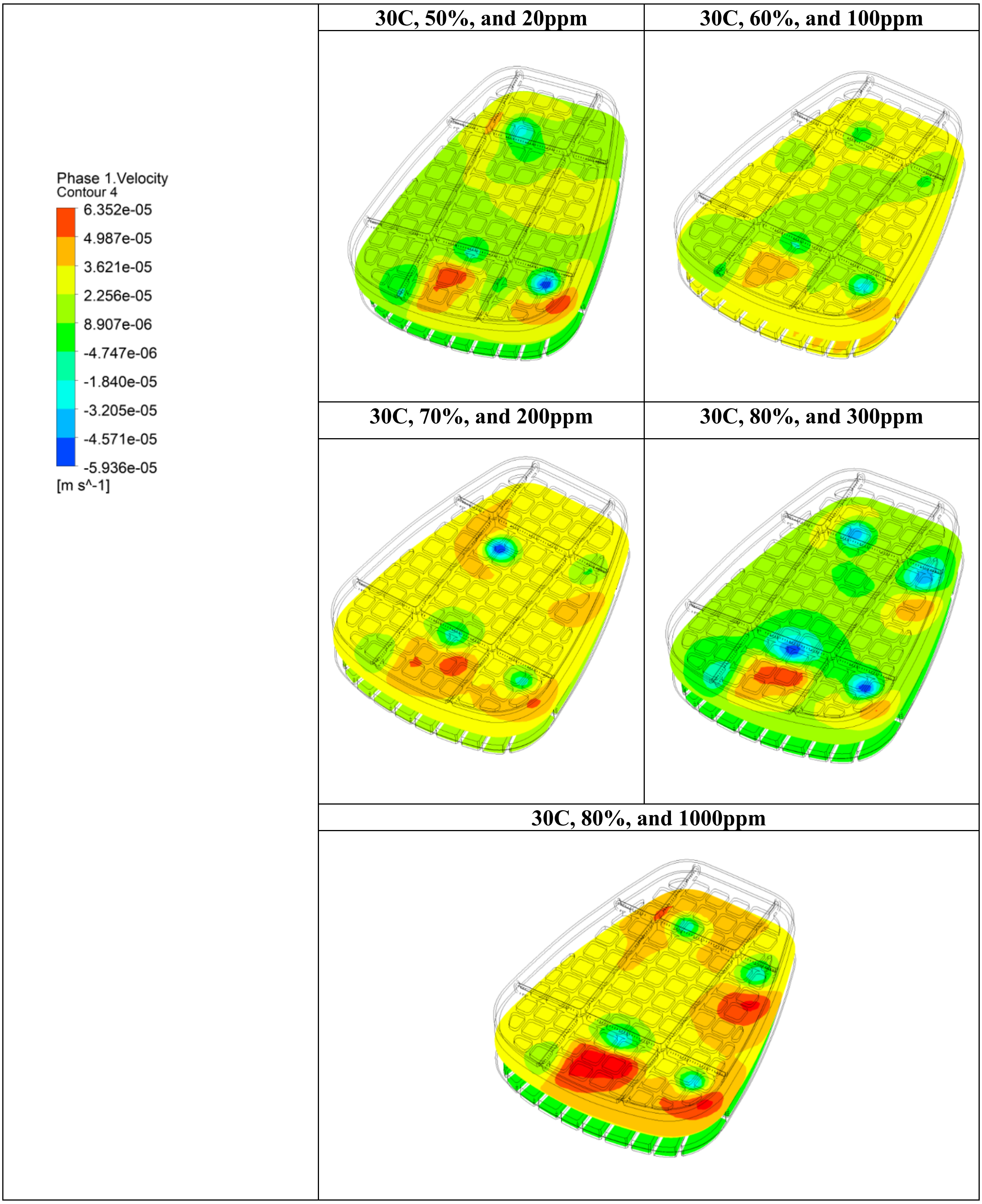

Fig. 8. Distribution of the velocity (a) Case I- Temperature at 30°C, the humidity of 50 % and filter concentration of 20ppm (b) Case II- Temperature at 30°C, the humidity of 60 % and filter concentration of 100ppm (c), Case III- Temperature at 30°C, the humidity of 70 % and filter concentration of 200ppm (d) Case IV- Temperature at 30°C, the humidity of 80 % and filter concentration of 300ppm (e)) Case V- Temperature at 30°C, the humidity of 80 % and filter concentration of 1000ppm

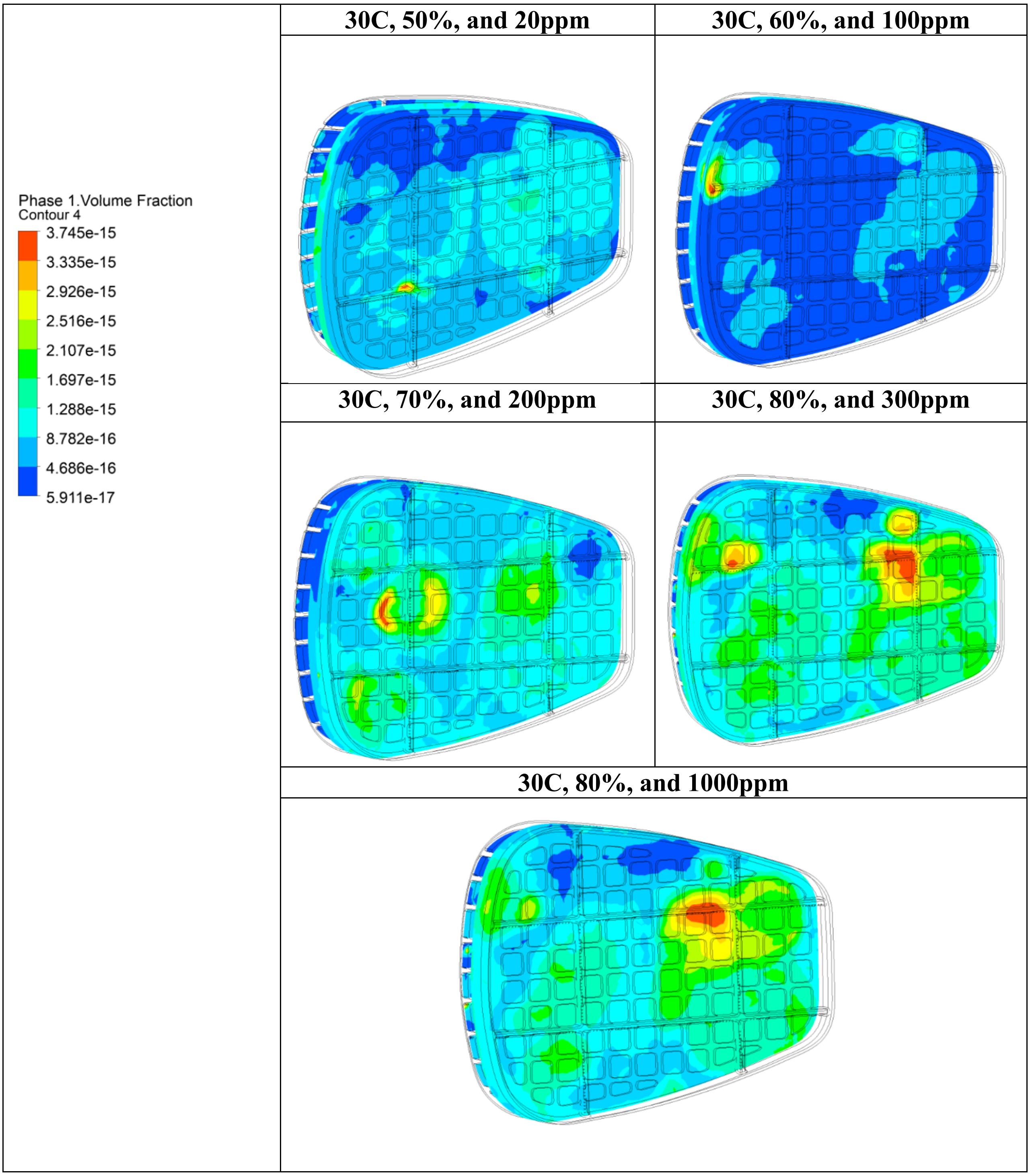

Fig. 9. Distribution of the volume fraction (a) Case I- Temperature at 30°C, the humidity of 50 %, and filter concentration of 20ppm (b) Case II- Temperature at 30°C, the humidity of 60 %, and filter concentration of 100ppm (c), Case III- Temperature at 30°C, the humidity of 70 % and filter concentration of 200ppm (d) Case IV- Temperature at 30°C, the humidity of 80 % and filter concentration of 300ppm (e)) Case V- Temperature at 30°C, the humidity of 80 % and filter concentration of 1000ppm

3.3 Velocity Effect on the Low Concentrated Filter under the High Humidity Condition

The fluid and particle are slightly hard to pass through the region of low velocity for a porous medium filter, especially in a humid climate. This phenomenon normally occurred due to the increases in the pressure and temperature in the charcoal filter which is prone to decrease the efficiency of the filtration concentration. The results show that the flow recirculation was observed in all cases, especially in the lower concentration of 20ppm and evenly distributed at the case 300ppm with 80% humidity. This recirculation of flow was presented in negative value as shown in the figure. This is due to the increase of the superficial velocity at the inlet which is prone to forming the dead zone. The region of the dead zone depicted the worst adsorption rate of the charcoal filter.

The highest velocities were also seen on the right side of the filter as compared to the other region of the charcoal filter. This is due to the fluid flow passing through the porous medium of the charcoal filter without any resistance as compares to other regions.

3.4 The Effect of Gas Mask Filter under High Humidity Conditions

The high humidity environment such as in Malaysia may pronely reduce the performance of the gas mask filter. This phenomenon may also reduce the life cycle of the gas mask filter and the filter should be changed frequently. The hot temperature and the high humidity of the environment worsen the lifetime of the filter. In this study, the ratio of the water vapor was set up within 50% to 80% with different concentrations of the filter being simulated. The humidity effect on the low concentrated filter is presented in volume fraction analysis as shown in Figure 9.
From the observation, the volume fraction was evenly distributed all over the charcoal filter. However, the highest fraction volume was seen for the case of 80% humidity and 1000ppm of concentration. However, the volume fraction increases when the concentration of the filter increases. This situation may reduce the absorption rate, especially on the right side of the filter which is prone to the presence of the dead zone. This is due to axial velocity diverting and circulating in low-velocity at that region. Furthermore, the increased ratio of humidity in the filter might reduce the absorption rate of the filter which the lifetime of the filter would be expired.

4. Conclusions

The effects of the pressure, velocity, temperature, humidity, and concentration on the gas mask filter were analyzed. The pressure drop is seen in the charcoal filter region which experiences high-velocity circulation. The high humidity ratio with the pressure drop in the gas mask filter also decreases the efficiency of filter concentration even though the temperature is constant. The high humidity ratio in the mask filter will retain the heat inside the gas mask filter, thus reducing the life cycle of the filter.

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