

Flow Characteristics of New Disposable Inhaler Spacer at Different Geometry

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Abstract: During the pandemic COVID-19, the data statistic stated there were patients with respiratory problem got infected. Due to the respiratory problem, the metered-dose inhaler and spacer were used as one of the treatment methods. The research objective is to identify the flow characteristics in the new disposable inhaler spacer and modify geometry of the disposable inhaler spacer to obtain desired velocity. The circular shape of model disposable inhaler spacer is selected among the previous researchers. The materials of new disposable inhaler spacer such as paper and polylactic acid (PLA) do not affect the flow characteristics. Several geometry models suppressed the fillet and chamfer to reduce the skewness below than 0.94. The flow characteristics such as turbulence kinetic energy (TKE), turbulence eddy dissipation (TED), velocity, particle velocity magnitude, streamline and vector velocity are obtained from the ANSYS Workbench Fluent 19.2 with the actual scale (1:1). The setup input data based on the selected parameters such as viscosity model, the properties of drugs (salbutamol and propellant), discrete phase model (DPM) equal to 80, boundary condition model and the method SIMPLE are based on the previous researcher. The nozzle injection used the dimension 0.49 millimeter for the five geometry models. The simulation work is verified with the result of previous simulation work. The transient flow used the 0.01 of time step size for 300 numbers of steps within an iteration. Key findings support that computational analysis can differentiate the complexity of the models. The trends of TED, TKE and velocity graph shown the approximately value between the model geometries. Overall, the study successfully achieved the desired velocity magnitude in term of visual and graph of the different geometry model. The future work that can used as benchmark to design new geometry model.

Keywords: Computational Fluid Dynamic (CFD), Flow characteristic, Metered-dose inhaler spacer

1. Introduction

Coronavirus disease also known as COVID-19 has increasingly spread caused of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). There are many people were infected and death included normal and chronic patient background [1-4] . There are many symptoms of COVID-19 recorded previous days. The most common symptom such as fever, dry cough, and fatigue. The other symptoms less common happened and might be some patient only such as loss of taste or smell, nasal congestion, red eyes, sore throat, headache, muscle or joint pain, different types of skin rash, nausea, diarrhea, and dizziness. For the quite severe COVID-19 disease, it included the shortness of breath, loss of appetite, confusion, pressure in the chest and more than 38 degree Celsius (WHO, 2020). Most of the COVID-19 patient were covered with self-isolation without any

medicine unless any related disease to the patients. The serious illness patients get into the intensive care unit (ICU) depending on the clinical of COVID-19. The several stages of COVID-19 were shown in Table 1.

Table 1 – Clinical stage of COVID-19 [5].

Stage	Explanation
1	Asymptomatic
2	Symptomatic and no pneumonia
3	Symptomatic and pneumonia
4	Symptomatic, pneumonia and oxygen required
5	Critically ill with multiorgan failure

The people who infected positive COVID-19 must be isolated at special room or space about 14 days before continuing the work as usual. Commonly, the serious case placed in the intensive care unit (ICU) as soon as possible. The best practices for all those who to keep

washing hand always and do not touch face skin with hand [6]. Always compulsory to use the face mask at any assemblage place. If possible, prevent to come any assembly program.

1.1 Human Respiratory System

The most inhalation process happens via nose. It through the series to the lungs. The series referred as the respiratory tract consists of upper respiratory and lower respiratory. The upper respiratory consist of nose, nasal cavity, mouth, pharynx, and larynx, while the lower respiratory comprise of trachea, bronchi, and lung [7].

Based on the statistic, about 10% of US children have asthma [8]. Advanced English Dictionary stated that respiratory disorder characterized by wheezing, usually of allergic origin. Asthma is a condition where the restriction of airways enters the body. The surrounding of airways was contracted and tighten. The air cannot move freely in and out the body. The effects such as coughing, wheezing and shortness in breath in (Structure and Functions of the Respiratory System, n.d.). The aerosol device is being used as treatment method. Due to the pandemic COVID19, there are many countries have replaced the small volume nebulizer (SVN) to pressurized metered-dose inhaler (pMDI) with spacer [9]. The focus only for patient who are elders and children.

1.2 Metered-Dose Inhaler (MDI)

Metered-dose inhaler (MDI) is a device that helps deliver a specific amount of medication to the lungs, usually by supplying a short burst of aerosolized medicine that is inhaled by the patient. The device helps to treat the asthma and chronic obstructive pulmonary disease (COPD). The small shape and easy to bring, safely, reliable and delivery consistent dosage [10]. The schematic view as shown in Fig. 1. The combination between MDI and spacer was produced the best drug delivery for targeted patient which are elders and children.

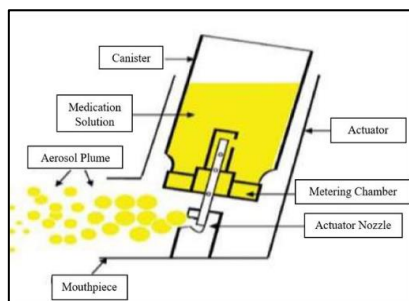


Fig. 1 – The cross-sectional of pMDI [11].

1.3 Nebulizer

Nebulizer is a one of treatment for respiratory problem. During the pandemic, the treatment was not suggested to use because of the risk of increase droplet contamination that can remain the air. It contributes to spread the COVID-19 to another patient [12]. It preferred

to use at home and located at low exposure place. Someone who practically use the device at home, the rules and advice must be followed. Locating the nebulizer near the window or increase air circulation [13].

1.4 Inhaler spacer

Inhaler spacer or valved-holding chamber (VHC) function as optimize the drug delivery time. It is very suitable for children and adult who inadequate to use actuator and inhalation technique. It also decrease the risk local effect [14]. The example of inhaler spacer and its position can be shown in Fig. 2.

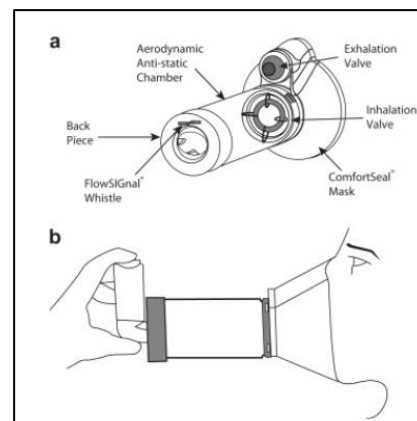


Fig. 2 – (a) VHC AeroChamber Plus® Z anti-static spacer (b) the proper position for MDI with spacer.

1.5 Disposable Inhaler Spacer

The disposable inhaler spacer referred to an item that can be disposed of after it has been used. The selection of material and shape influenced the decompose of the product. The previous research preferred disposable spacer for asthma patient [15]. It also can reduce the large particle fraction and maximize the fine particle to the airways [16]. The suitable step to practice while breathing using spacer or VHC, slow and deep inhalation and then breath hold is optimal. 15 L.min^{-1} is minimum while the optimum flowrate is 30 L.min^{-1} . The example of disposable inhaler spacer has been commercialized in the market as in Fig. 3. The purpose of this research article was to identify the flow characteristics in the new disposable inhaler spacer. The references based on the example of streamline and velocity vector.



Fig. 3 – (a) The commercial DispoZABLE spacer [17].

1.6 Analysis of Flow Characteristics

The purpose of this research article was to identify the flow characteristics in the new disposable inhaler spacer. The references based on the example of streamline and velocity vector. The findings related to streamline, velocity vector, turbulence kinetic energy, turbulence energy dissipation and velocity.

2. Methodology

2.1 Design the Fluid Domain

The design of five-unit geometry model was done in SOLIDWORK 2019. The model referred to the previous researcher. The researcher was made comparison with the commercial product DispoZABLE spacer in the previous journal. The comparison of shape can be shown in Fig. 4(a) and Fig. 4(b).

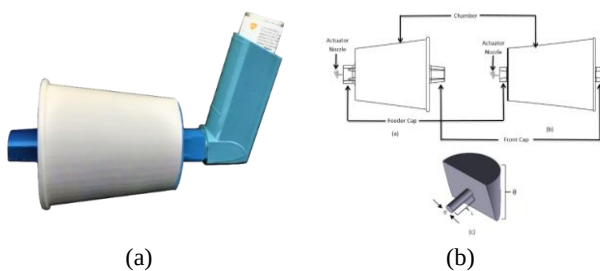


Fig. 4 – (a) Disposable inhaler spacer, AeroCup attach with MDI; (b) Shape comparison between AeroCup and DispoZABLE inhaler spacer. (c) the internal part of actuator nozzle [14].

Based on the previous researcher, the dimension of actuator nozzle set with diameter of the orifice is 0.49 mm, the length orifice is 1.50 mm and the angle of actuator is 165 degree [14]. There are five-unit model geometries for new disposable inhaler spacer. Each model has different geometry and material. In this scope, the study only covers the flow characteristics which fluid domain while the material did not affect the flow characteristics.

According to the Fig. 5, there were a similar shape but different size and material. Model 1 consist of PLA and paper while model 2 only fully paper. The lower side shown the fluid domain for simulation analysis. The first model can assemble the parts but cannot for the model 2.

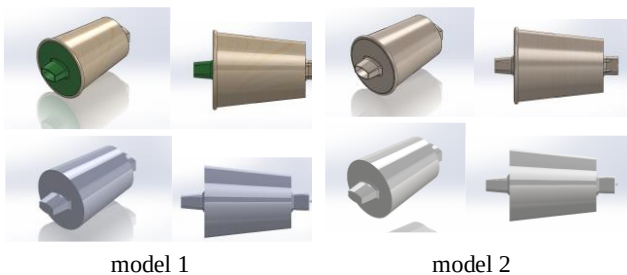


Fig. 5 – Geometry for model 1 and model 2

Based on the Fig. 6, the model 3 and model 4 shown similar shape of chamber but different size, material, and position of feeder cap. The internal position for feeder cap in model 4 compare than model 3. The model 3 consist of PLA (green) and paper while model 4 only fully of paper. The lower side shown the fluid domain for simulation analysis.

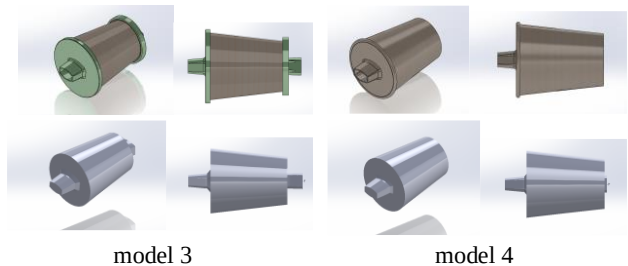


Fig. 6 – Geometry for model 3 and model 4

Based on the Fig. 7, the model shown rectangular shape of chamber. different size, The paper as material and internal position for feeder cap toward the front cap. It also fully of paper. The model cannot disassemble.

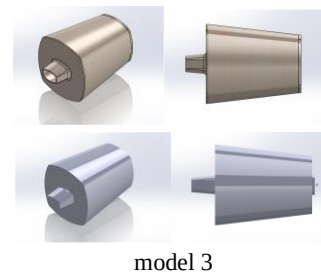


Fig. 6 – Geometry for model 5

2.2 Grid Independent Test (GIT)

For all geometry model, it shown the GIT nine (9) suitable selection for the further simulation because the lowest value of skewness and highest value of orthogonal mesh metric were the best criterion. The sample GIT for the first model was shown in Table 2. After finished all the GIT for the five-geometry model, the finalized value of GIT of each geometry model was shown Table 3. The highest value of skewness and lowest skewness were 0.93454 (model 1) and 0.88444 (model 2). Most of the selection were the last grid.

Table 2 – Grid independent test for geometry model 1

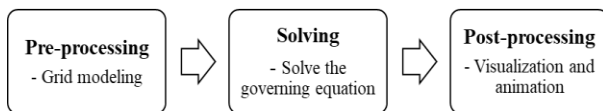
Grid	No. of nodes	No. of elements	Skewness matric	Orthogonal matric
1	40977	211375	0.99721	0.99457
2	40996	211582	0.99716	0.99185
3	41163	212449	0.99708	0.99296
4	41303	213208	0.99714	0.99192
5	41619	214670	0.99763	0.99146
6	42401	218762	0.99804	0.99775
7	44436	229256	0.99388	0.99293
8	50565	260777	0.97842	0.99109
9	79112	411551	0.93454	0.99

Table 3 – The final selection GIT for every geometry

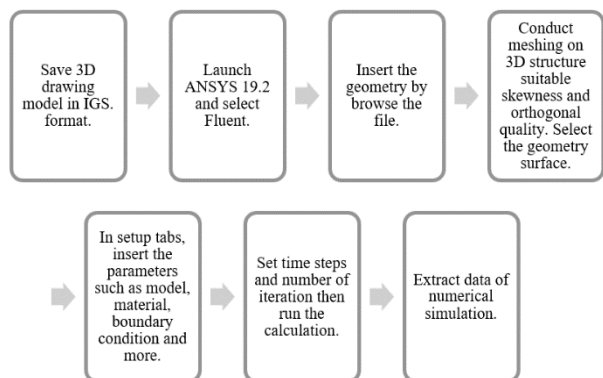
Grid	No. of nodes	No. of elements	Skewness matric	Orthogonal matric
1	79112	411551	0.93454	0.99
2	136557	716009	0.88444	0.99348
3	135628	713101	0.90403	0.99403
8	144084	760235	0.89182	0.99664
9	162044	858018	0.89331	0.99512

2.3 Computational Simulation Analysis using ANSYS Fluent 19.2

The study involved of software SOLIDWORKS 2019 (Dassault Syst me) for designation of disposable inhaler spacer. The modification of front cap, chamber, and feeder cap in different appearance and internal dimension. The process in the computational fluid analysis follows the basic steps as available in ANSYS Fluent. The geometry from the SOLIDWORK which originally save as. SLDPRT file must be converted to the .IGS format. This format can be generated by ANSYS software. The process begins with grid modeling in pre-processing, then followed by solving the governing equation and lastly post-processing. The stage of ANSYS simulation was shown in Fig. 7.


Fig. 7 – The stage of ANSYS simulation

After the 3D drawing model of new disposable inhaler spacer inserted in the software, conduct the meshing to the model. Find the suitable skewness and orthogonal quality. Record the nine data to create the simple grid independent test (GIT). After getting the suitable value, setup the parameters such as model, material, boundary condition, discrete phase and more. Set the time steps and number of iterations as 0.01 and 1 before running the calculation. Extract the data of numerical simulation after complete. The flow process of setup the computational analysis was shown in Fig. 8.


Fig. 8 – Flow process of setup the computational analysis

3. Results and Discussion

3.1 Comparison to the Simulation Study

The results and discussion section presents data and analysis of the study. Comparison between AeroCup and new inhaler spacer were carried out. The analysis of relative error was taken on the particle velocity and air temperature of the geometry model 1. Based on the Table 4, the velocity inlet was set as 100m/s in the setup. There are two variable parameters selected for such particle velocity magnitude and air temperature. There two other parameters such as HFA mass fraction and velocity will be improving for the next research in recommendation. The value of particle velocity magnitude for AeroCup stated as 28.421 m/s while for the new inhaler spacer equal to 28.37606. both of result using the ANSYS 19.2. There are only 0.158 percent of relative error.

Table 4 – Verification of geometry model

Inlet vel. (m/s)	Parameters	Reference simulation [10]	Current simulation	Error (%)
100	Particle velocity magnitude (m/s)	28.421	28.3760	0.158
	Air temperature (K)	293.01	297.029	1.353

3.2 Turbulence Eddy dissipation

Fig. 9 shows the graph turbulence eddy dissipation versus the position of z-axis for five unit of new disposable inhaler spacer. The interpretation begins with model geometry 1. It started at the peak (blue arrow) about 820,000 (m^2s^{-3}). The peak went down sharply from -0.02m distance to 0.017m (green arrow) and remained steady at 0 (m^2s^{-3}) afterwards until 0.15m. The trend for model geometry 2 and model geometry 3 was quite similar with geometry model 1 but the peak turbulence eddy dissipation for model 2 was 780,000 (m^2s^{-3}) which a bit lower while the peak for geometry model 3 was 540,000 (m^2s^{-3}) also lower than the previous. The three-geometry model (model 1,2 and 3) has the same circular round of chamber.

The geometry model 4 started at the peak (blue arrow) about 900,000 (m^2s^{-3}). The peak went down sharply from -0.005m distance to 0.00m (green arrow) and remained steady at 0 (m^2s^{-3}) afterwards until 0.15m. The trend for model geometry 5 was quite similar but the peak turbulence eddy dissipation for model 5 was 620,000 (m^2s^{-3}). The peak went down sharply from -0.005m distance to -0.002m (green arrow) and remained steady at 0 (m^2s^{-3}) afterwards until 0.15m. Both geometry model 4 and model 5 has same internal feeder caps but different shape of chamber.

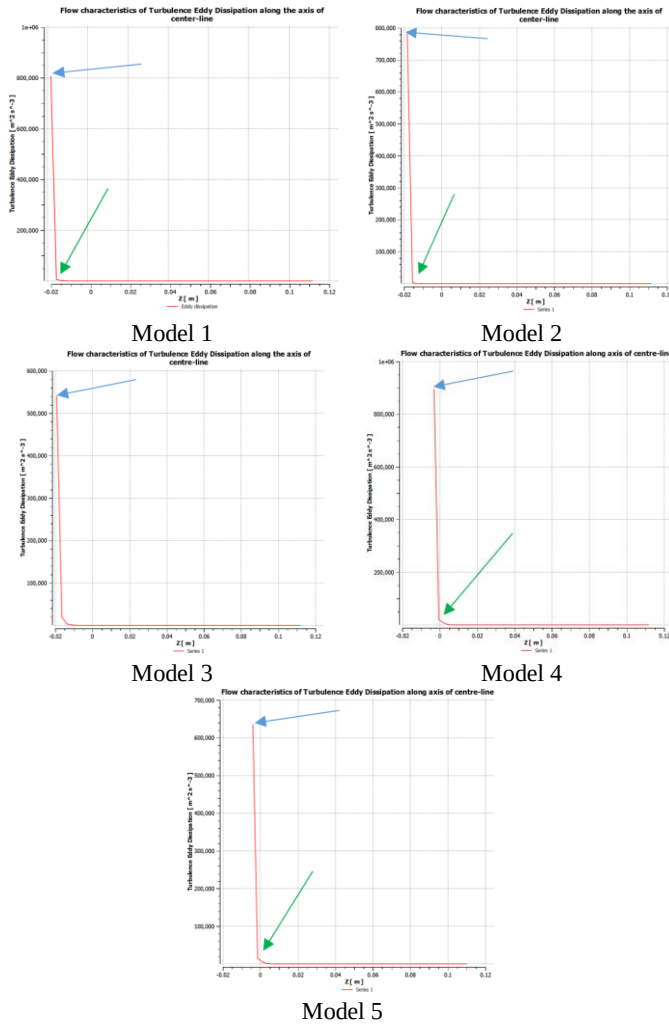


Fig. 9 – Flow characteristics of turbulence eddy dissipation along the axis of centreline

Table 5 shows the value of turbulence eddy dissipation. The table was analyzed based on the maximum value in the middle plane of the new disposable inhaler spacer. The geometry model 5 has the highest value followed by model 3, model 1, model and model 4. There was a large different for geometry model 5 compared to the other. The chamber shape like rectangular while the others with circular shape.

Table 5 – Turbulence kinetic energy at middle plane

Model	Turbulence kinetic energy (m^2s^{-2})
1	59.4497
2	56.7761
3	54.5883
4	60.2534
5	121.767

3.3 Velocity

The study on the velocity versus the position of z-axis. Based on the Fig.10, the geometry model 1 started at the peak (blue arrow) approximately 21.3 ms^{-1} designate as highest flow velocity. The velocity was sharply fall from -0.018m distance to -0.016m (green

arrow). The velocity flow became raised about 1.7 ms^{-1} at -0.04m (orange arrow). Then, the velocity gradually dropped and remained small fluctuated to 0 ms^{-1} until 0.15m. The trend for model 2 was quite similar with model 1 but the peak turbulence eddy dissipation for model 2 was 21.7 ms^{-1} which a bit higher. The velocity flow became raised about 1.6 ms^{-1} at -0.01m. Then, the velocity gradually dropped and remained small fluctuated to 0 ms^{-1} afterwards until 0.15m.

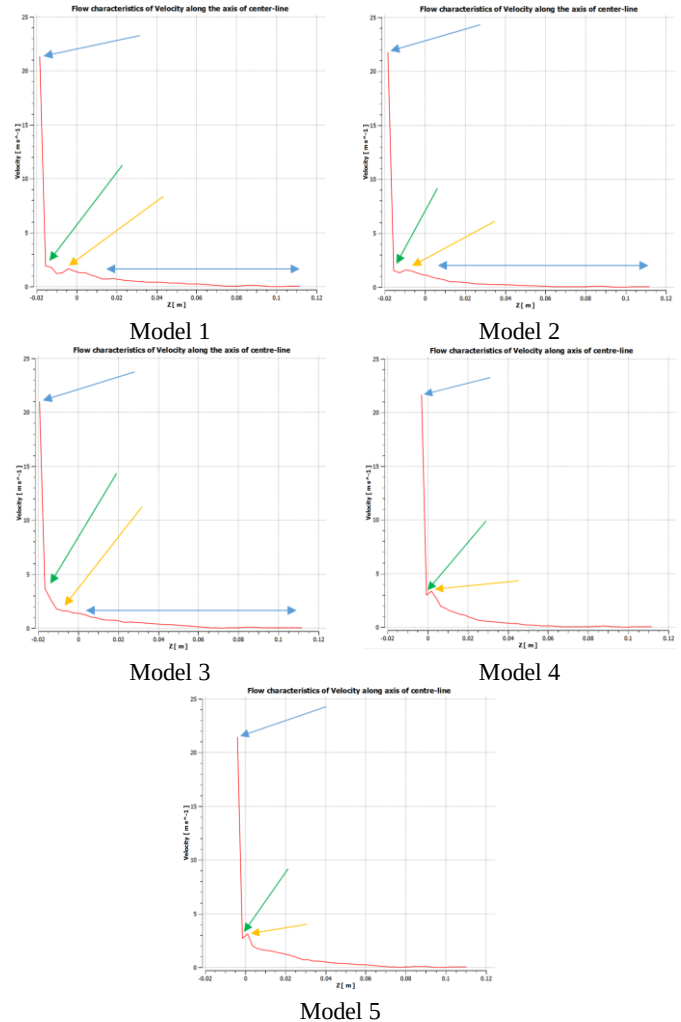


Fig. 10 – Flow characteristics of velocity along the axis of centreline

The geometry model 3 has a peak velocity flow approximately 21.0 ms^{-1} . The velocity was sharply fall from -0.019m distance to -0.017 m. The velocity flow dropped to 1.7 ms^{-1} at distance -0.012 m. Then, the velocity gradually dropped and remained small fluctuated to 0 ms^{-1} afterwards until 0.15m. The geometry model 4 started at the peak approximately 21.5 ms^{-1} . The velocity was sharply fall from -0.003m distance to -0.001m. The velocity flow became raised about 3.4 ms^{-1} at -0.003 m. Then, the velocity gradually dropped and remained small fluctuated to 0 ms^{-1} afterwards until 0.15m. The velocity flow became raised 3.2 ms^{-1} at -0.002 m. Then, the velocity gradually dropped and remained small fluctuated to 0 ms^{-1} afterwards until 0.15m.

Based on the result of velocity against the position of z-axis, the geometry influencing the velocity flow in the inhaler spacer.

3.4 Particle Velocity Magnitude

The particle velocity magnitude can be selected in the graphic result after finished the simulation. The value of velocity magnitude is based on the discrete particle model (DPM). Based on the Fig. 11, the particle velocity magnitude of drugs delivery for all geometry models given as shown Table 6. The table was analyzed based on the maximum value in the middle plane of the new disposable inhaler spacer.

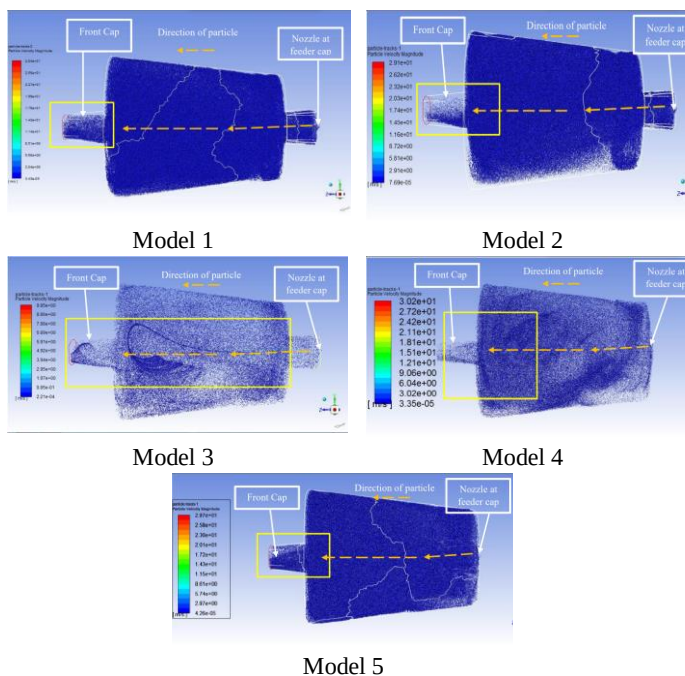


Fig. 11 – Flow characteristics of velocity along the axis of centreline

Table 6 – Particle velocity magnitude in the middle plane

Model	Particle velocity magnitude (ms^{-1})
1	29.7418
2	29.7955
3	29.9587
4	29.9469
5	30.2134

Model 1 shown the fully drug particle delivery from the nozzle to the front caps. All the space of chamber has been fulfilled with the particles. The maximum value of particle velocity was 29.7418 ms^{-1} . The particle velocity of geometry model 2, model 3 and model 4 equal to 29.7955 ms^{-1} , 29.9587 ms^{-1} and 29.9469 ms^{-1} . The result shown the highest particle velocity was geometry model 5 equal to 30.2134 ms^{-1} . Yellow rectangle represented the highlight area.

The particle moved from the nozzle at the back to the front of the inhaler spacer (dash arrow). The geometry 1 shown particle did not fulfil the front cap area at the time (yellow rectangle) but it successful passed it. The pattern of model 2 was quite similar with previous where completely fulfilled and passed the front cap. The model 3 shown the rotation movement of particle clearly in the chamber (yellow rectangle). The particle also fully completes the throughout the spacer. There was rotation particle in the model 4. The position of feeder cap was in the internal chamber toward to front cap. The position also applied to the model 5. The model 5 shown the best particle fulfilled in the chamber. The highest value of particle velocity related to the completeness in the inhaler spacer for model 5.

3.5 Streamline

In this study, streamline referred as the flow of massless particle through the entire fluid domain. The previous research stated that the purpose of the streamline figures out the flow around and wake up the module. In the post-processing, the streamline can be setup with various variable. The results shown in the Fig. 12. The model 1 shown the movement of streamline more circulation due to the collision of flow to the wall in chamber. Most of the streamline in the chamber has the normal value of velocity depends on the color of the streamline. At the begins of the nozzle, the velocity was high compared to after getting into chamber. The pattern quite similar with the model 1 with velocity but has highest value of streamline velocity at middle of the inhaler spacer. Then, the geometry model 4 followed with 28.3002 ms^{-1} . The internal position of feeder cap of model 4 and model 5 achieved the higher velocity value of streamline compared to geometry model 3.

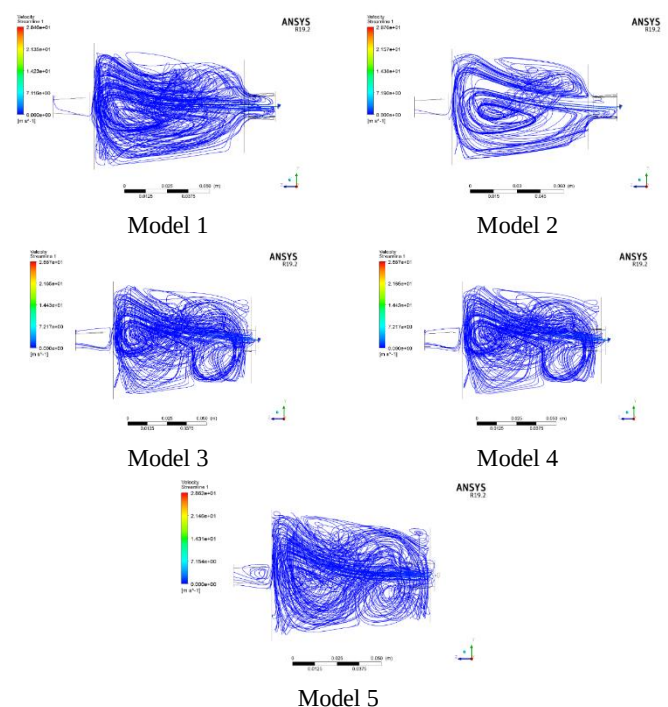


Fig. 12 – The streamline of geometries model

The Table 7 was analyzed based on the maximum value in the middle plane of the new disposable inhaler spacer.

Table 7 – Streamline in the middle plane

Model	Streamline (ms ⁻¹)
1	28.0317
2	28.352
3	28.0836
4	28.3002
5	28.2384

3.6 Velocity Vector

The study referred to velocity vector applied to the new disposable inhaler spacer. The selection of vector has been made in the post-processing stage. The setup of velocity vector begins by selecting the vector. All fluid domains were selected with identify the vector at the middle plane (plane 1). The type of sampling as vertex with 1.0 reduction factor. The selected velocity as a variable, while arrowhead 3D set as the arrow symbol. This setup was applied to all geometry's models. The velocity vector was shown in the Fig. 13 while Table 8 shown as result of velocity vector. The table was analyzed based on the maximum value in the middle plane of the new disposable inhaler spacer.

After analyzed the velocity vector, there was about nine flow circulation (small and large circulation) happened in the geometry model 1. The flow separation happened at every between circulation there. For example, flow from nozzle was separated into three parts (rectangle with number three, four and six).

Table 8 – Velocity vector in the middle plane

Model	Streamline (ms ⁻¹)
1	28.0317
2	28.352
3	28.0836
4	28.3002
5	28.2384

The geometry model 2 has about eight flow circulation with velocity vector equal to 29.7955 ms⁻¹. Geometry model 3 has similar amount of flow circulation with model 2 but the velocity a little bit large as 29.9587 ms⁻¹. For the internal feeder cap, there were a different between geometry model 4 and model 5 in term of velocity magnitude. The location flow circulation approximately same but the velocity model 5 highest than others. The velocity vector of model 5 was 30.2134 ms⁻¹, while the model 4 equal to 29.9469 ms⁻¹. The average of all the geometries has eight flow circulation. More flow circulation suitable to provide more time for children and elders to inhale easily. The both elders and children were difficult to practice the inhalation technique.

4. Conclusion

This study has already compared three main different designs which are to evaluate their aerodynamic performance. This study was verified the flow characteristics between current new spacer design and previous AeroCup 1.0 model. The study was modified geometry of the disposable inhaler spacer to obtain desired velocity and identified the flow characteristics at the different geometry. The result of present simulation was verified with the previous study about 0.158 percent of relative error at present outlet velocity and previous outlet velocity equal to 28.37606 ms⁻¹ and 28.421 ms⁻¹. There were modified the geometry shape into five types of geometries model.

The flow characteristics such as turbulence kinetic energy (TKE), turbulence eddy dissipation (TED), velocity, particle velocity magnitude, streamline and vector velocity were obtained from the ANSYS Fluent 19.2 result in post-processing. The graphs and visualization were attached in the section 3.0. The result of TED for model 1 to 5 given as follows; 2.04178e+06 m²s⁻³, 1.84679e+06 m²s⁻³, 7.3689e+06 m²s⁻³, 1.82472e+06 m²s⁻³ and 1.6515e+07 m²s⁻³. The TKE for model 1 to 5 are equal to 59.4497 m²s⁻², 56.7761 m²s⁻², 54.5883 m²s⁻², 60.2534 m²s⁻² and 121.767 m²s⁻² respectively. The different pattern of visualization for particle velocity magnitude and vector field were based on the same value of velocity.

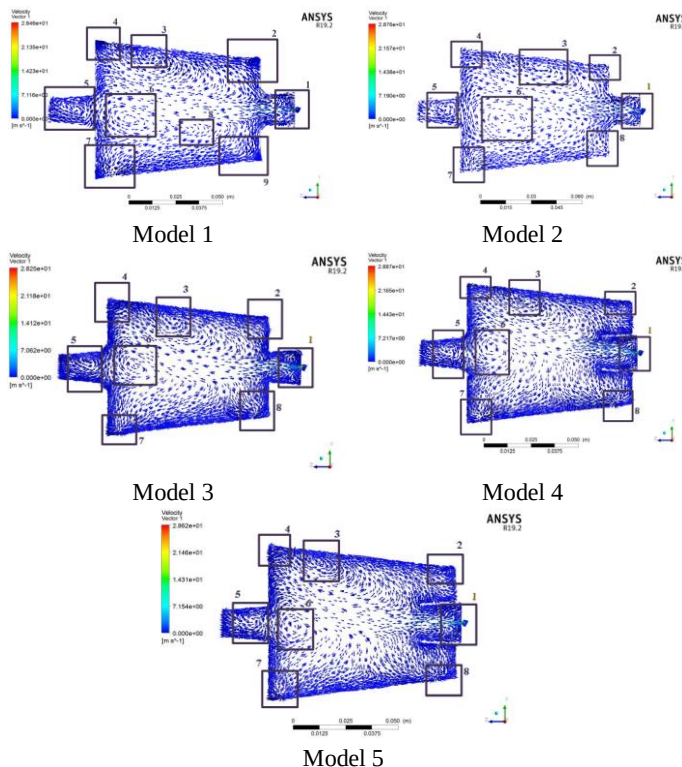


Fig. 13 – Velocity vector of geometries model

In according to velocity vector, model 1 shown the distribution of velocity vector along z-axis. The flow velocity at relatively low. The flow begins from the nozzle to the chamber. The flow collides with the wall then circulate and throughout any direction before reach to the outlet outflow.

The different of geometry for every model produced the different flow characteristics. The model 1, model 2 and model 3 shown the approximately flow characteristics due to the same shape of inhaler spacer. The model 4 and model 5 has the same internal feeder cap produced the approximately velocity vector at the middle of the plane created but different pattern for streamline and particle velocity magnitude. The rectangular shape of model 5 produced highest velocity compared than other. Overall, the study conducted hopes to bring an in-depth knowledge on the flow characteristic for other shapes included the flexibility origami geometry to delivery drug by disposable inhaler spacer at optimum for the targeted patients.

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