

The Flow Characteristic of Simulation for Newly Developed Disposable Inhaler Spacer Geometry

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Abstract

Pressurized metered-dose inhalers (pMDIs) are widely used for airway disease treatment, but incorrect usage reduces their efficiency, with much of the drug depositing in the oropharynx. Spacer devices were developed to slow aerosol particles and improve lung deposition. This study compares four spacer designs using Computational Fluid Dynamics (CFD) in SolidWorks 2024, focusing on outlet velocity and pressure. Results showed that WT-Model 4 provided the most efficient and uniform airflow distribution, with velocities ranging from 0.361–1.874 m/s (average 1.628 m/s) and stable outlet pressures around 101324.84 Pa, indicating improved aerodynamic performance and drug delivery potential.

1. Introduction

Asthma is a chronic inflammatory disease of the respiratory system, marked by airway narrowing, mucus overproduction, and breathing difficulties, which significantly impair quality of life. Pressurized metered-dose inhalers (pMDIs) are widely used, but their efficiency is limited by improper technique and high particle velocity, leading to oropharyngeal deposition and side effects [1]. Asthma symptoms may resolve with or without treatment; however, exacerbations can be life-threatening. Chronic airway inflammation and hyperreactivity often persist even in asymptomatic periods, though they may improve with therapy [1]. The link between severe asthma and COVID-19 remains debated. It is unclear whether asthma increases susceptibility to severe SARS-CoV-2 outcomes or offers some protection, and the extent to which infection triggers asthma attacks is still uncertain [2].

COVID-19 can progress to acute respiratory distress syndrome (ARDS) in about 5% of cases, with mortality rates ranging from 30% to 60%. Mechanical ventilation is the main supportive therapy, aiming to optimize gas exchange and reduce ventilator-induced lung injury [3]. During the pandemic, pMDIs and dry powder inhalers were preferred over nebulizers, as nebulization increases the risk of SARS-CoV-2 aerosolization and transmission [4]. Asthma remains a major health issue in Malaysia, with prevalence rates of 8.9–13.0% in children and 6.3% in adults, and mortality rising by 0.6% annually since 1990 [5]. Asthma and chronic obstructive pulmonary disease (COPD) are obstructive airway disorders that may coexist as asthma-COPD overlap syndrome (ACOS), which affects 15–25% of COPD patients and is linked to persistent airflow limitation, hyperresponsiveness, and frequent exacerbations [6–8]. Asthma is also among the most common chronic diseases in children (6–9%), influenced by genetics and environmental factors such as smoking, air pollution, and obesity. Smoking, particularly among women and children, worsens symptom control and reduces treatment effectiveness [9]. The pressurized metered-dose inhaler (pMDI), introduced in the 1950s, revolutionized therapy for airway diseases, though only ~20% of the dose reaches the lungs. Spacers and valved

holding chambers (VHCs) were developed to improve drug delivery by reducing oropharyngeal deposition and allowing easier inhalation [10].

2. Methodology

The flow properties and particle deposition behavior of a recently created disposable inhaler spacer are assessed in this work using a computational method. The simulation-based approach aims to optimize spacer design for efficient medication administration by offering a thorough examination of airflow behavior under varied settings. In the meantime, the inhaler spacer's 3D shape was designed and developed using SolidWorks 2021. SolidWorks is used in this thesis to make the model easier to grasp and see. This study specifically focuses on analyzing the outlet of the spacer, as it directly influences airflow behavior and drug delivery efficiency. Considering the velocity at the mouthpiece directly affects how well the drug enters the patient's lungs, it is critical to ascertain the outflow velocity for each spacer. The speed and dispersion of particles at the exit are influenced by the flow characteristics produced by various spacer geometry. The effectiveness of each design's drug delivery can be compared by examining the outflow velocity. Drug particles may accumulate in the mouth and throat if the velocity is too high, and the medication may not enter the respiratory tract deeply if the velocity is too low.

2.1 Synthesis of Method

To determine which spacer strikes the best balance between enhancing drug deposition in the lungs and reducing drug loss in the upper airway, it is crucial to assess the outlet velocity. The assessment of outlet velocity serves as a crucial part of the methodology. The outlet velocity directly influences how effectively aerosolized drug particles are delivered to the lower respiratory tract, while also determining the extent of drug loss in the upper airway. By focusing on this parameter, the research aims to identify which spacer design achieves the best balance between enhancing drug deposition in the lungs and minimizing deposition in the mouth and throat. This method, which combines computational modeling with velocity analysis, ensures that the evaluation of spacer performance is both comprehensive and clinically relevant.

2.2 Simulation

In previous research, the fundamental results and dimensional parameters of the spacer designs were already established and documented. These earlier studies provided the baseline geometry and initial performance data, which serve as valuable references for the present work. Building on this foundation, the current study takes the next step by experimenting further with these results through detailed computational fluid dynamics (CFD) simulations. By applying advanced analysis on airflow velocity, pressure distribution, and flow trajectories, this research aims to generate additional insights into the performance of each spacer model. Such an approach not only validates the findings of earlier studies but also extends them, offering a deeper understanding of how different spacer geometries influence drug delivery efficiency. Ultimately, this continuation of prior work ensures that the newly developed disposable inhaler spacer can be optimized more effectively for clinical applications.

2.3 Design

SolidWorks 2021 was employed to design and develop the three-dimensional geometry of the inhaler spacer. This software was selected because it provides precise control over dimensions, shapes, and structural features, ensuring that the design meets the intended specifications of the study. By generating realistic 3D representations, SolidWorks made it easier to understand the design concept, identify potential weaknesses, and prepare the model for computational fluid dynamics (CFD) analysis.

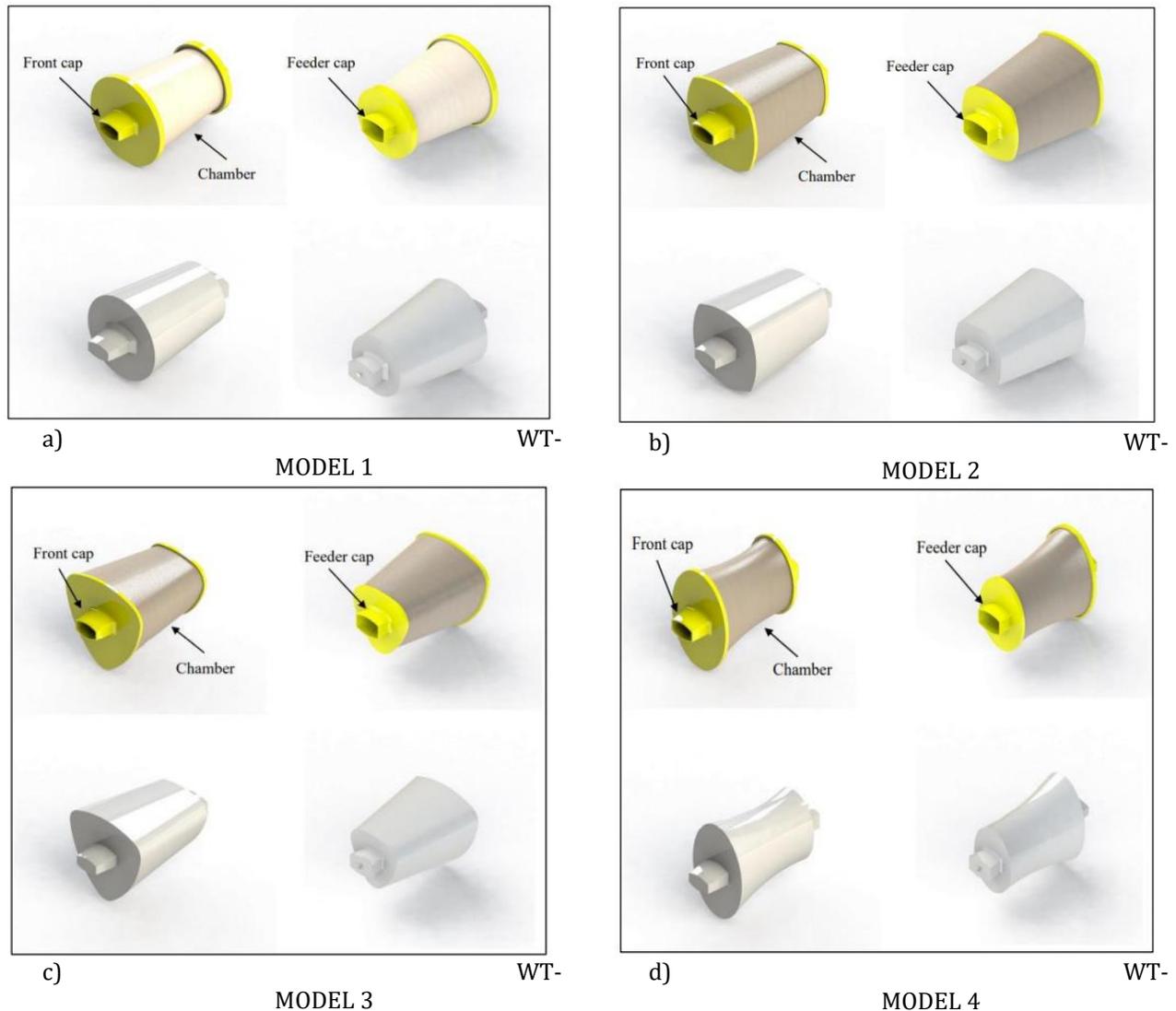


Fig 1 Design of Each Spacer

2.3 CFD Using Solidwork Software

Computational Fluid Dynamics (CFD) was applied to analyze, visualize, and interpret the flow behavior within the newly developed spacer model. Through CFD, key data such as velocity, pressure distribution, and overall airflow patterns were extracted, allowing for a comprehensive understanding of how the design influences drug delivery performance. The simulation process makes it possible to replicate real-life inhalation conditions without the need for time consuming physical experiments. By serving as a digital platform, CFD provides a reliable medium for studying fluid dynamics and identifying critical factors recirculation zones, and pressure losses. This capability is particularly valuable to engineers and researchers, as it allows them to predict airflow behavior accurately, compare alternative designs, and optimize the spacer's geometry before moving toward physical prototyping.

2.4 Velocity Streamline

In this research we will indicate the previous thesis and compare with the results had taken. There are numerous swirl and recirculation zones. Recirculation occurs when swirl states twist and the particle flow moves about in the spacer and the outlet velocity once more. Through the use of disposable spacers M1, M2, M4, and M3, some designs create more stable and streamlined flow with reduced velocity, while others generate stronger recirculation zones. Through this comparative analysis, the study aims to determine which spacer design minimizes recirculation losses and ensures a more consistent outlet velocity. Ultimately, these findings contribute to identifying the most effective geometry for enhancing drug deposition in the lungs while reducing particle loss within the spacer chamber.

2.5 Velocity Contours

The velocity contour is a visual representation of airflow speed within the inhaler spacer, expressed through colour gradients that indicate regions of high and low velocity. This analysis is crucial as it reveals the distribution of airflow, the presence of recirculation zones, and the uniformity of flow at the outlet. By examining these contours, it becomes possible to evaluate how effectively each spacer design channels airflow toward the outlet. A smoother and more uniform velocity distribution generally indicates a design that enhances drug delivery to the lungs while minimizing losses in the upper airway. Therefore, velocity contour analysis serves as an essential tool for comparing different spacer geometries and identifying the most efficient design.

3. Result and Discussion

This section investigated and discussed the simulation's findings. To understand the flow behavior, the simulated model was used to analyze the four designs. To help with comprehension of the flow, all of the data was arranged into tables and graphs. In the previous chapter, the simulations used to obtain the conclusions are explained and contrasted as technique. This findings will be compare and discussed to simulate in SolidWork for the newly developed disposable inhaler spacer geometry .

3.1 The Velocity Analysis at Outlet

A recommended outlet velocity might be somewhere between 1 to 6 m/s, with many devices being toward the lower end (~2-5 m/s) for comfort and efficiency. For this assumed that the inlet is 1 m/s for each outlet. The surface area of the outlet is 0.0003 m^2 . The data shown the outlet of each model that stimulated A horizontal line was sketched at the outlet each of the spacer, positioned at the nozzle section.

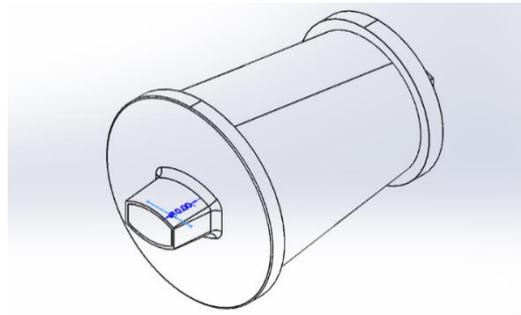


Fig 2 A Horizontal Line Was Sketched At The Outlet Each Of The Spacer

Table 1 Outlet Velocity Data

WT-Model	Minimum m/s	Maximum m/s	Average m/s	Bulk Average m/s
1	0.980	1.816	1.628	1.644
2	0.727	1.880	1.629	1.654
3	0.743	1.886	1.627	1.652
4	0.361	1.874	1.628	1.653

The analysis suggests that WT-Model 1 provides the most balanced performance, with an outlet velocity that is both stable and within the optimal range for inhalation therapy. It's narrower distribution of velocity values makes it the most reliable option for ensuring consistent drug delivery efficiency and improved patient safety compared to the other models.

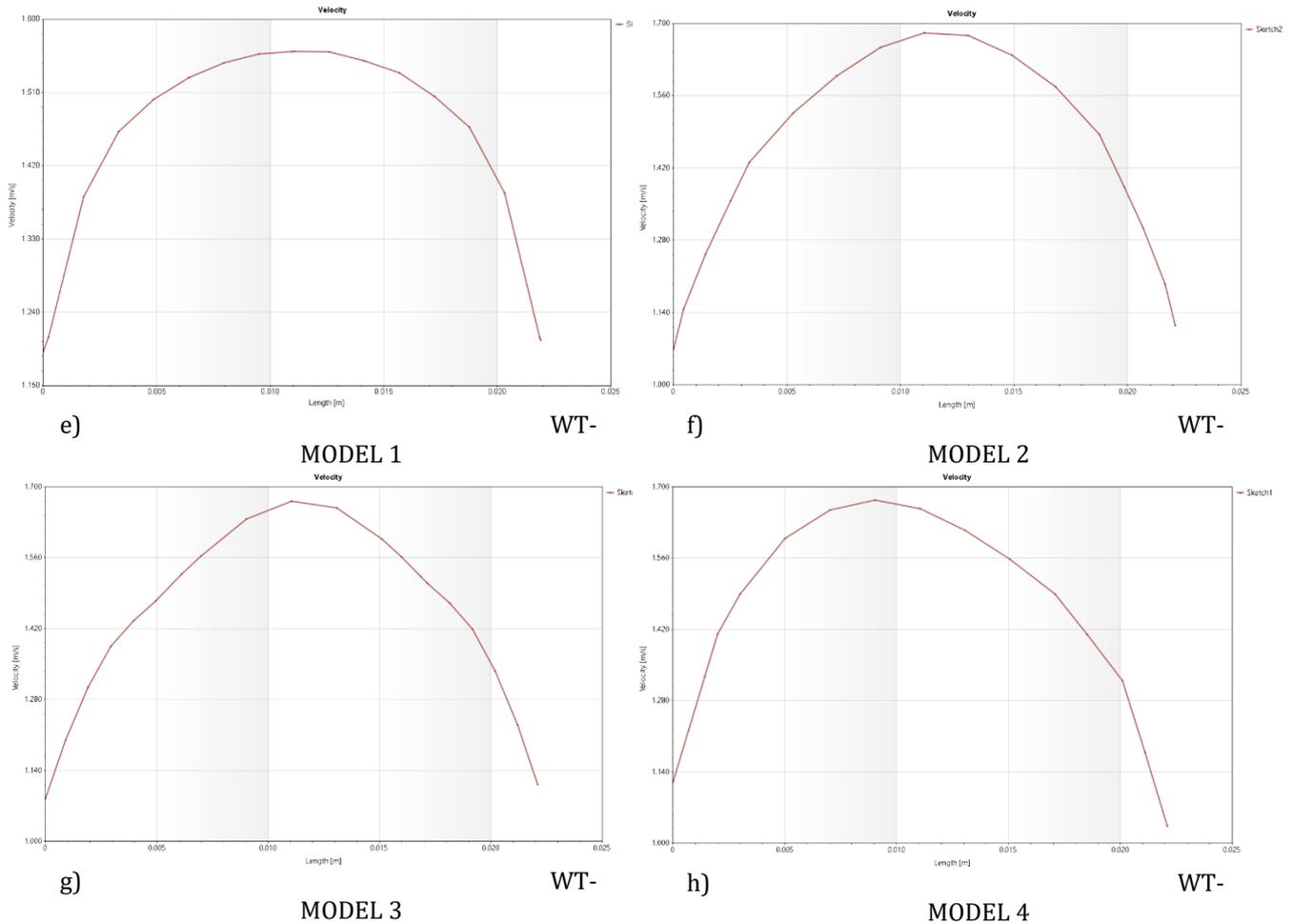
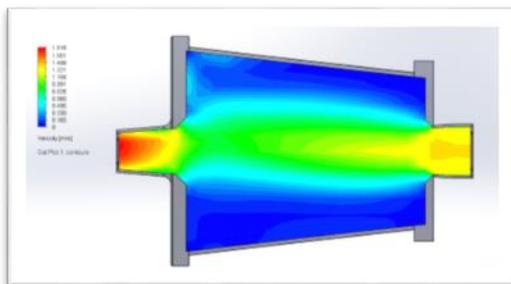


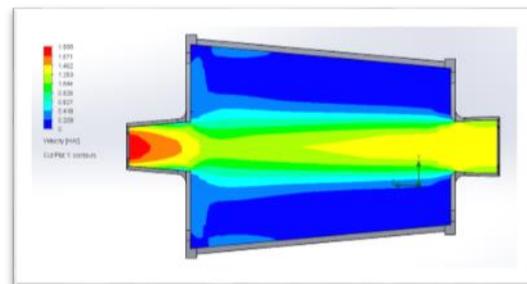
Fig 3 Graph Outlet Velocity

3.2 The Outlet Velocity Distribution of Contour Analysis

Contour plots of the four spacer geometries (WT-MODEL 1–4) revealed distinct airflow characteristics affecting aerosol delivery. WT-MODEL 1 showed relatively uniform distribution with minor wall turbulence, offering stability but risking deposition losses. WT-MODEL 2 produced a centralized jet that reduced wall deposition and aligned with the breathing pathway, though excessive velocity could reduce comfort. WT-MODEL 3 displayed irregular gradients and turbulence, leading to poor mixing, uneven airflow, and higher deposition risk. In contrast, WT-MODEL 4 achieved the most uniform and balanced outlet profile, minimizing turbulence and losses while ensuring effective airflow for drug delivery. Overall, WT-MODEL 4 demonstrated the best aerodynamic performance, while WT-MODEL 3 performed the worst. WT-MODEL 1 and 2 showed moderate efficacy, with WT-MODEL 1 providing stable but slightly turbulent flow and WT-MODEL 2 favoring centralized distribution.



i) WT-MODEL 1



j) WT-MODEL 2

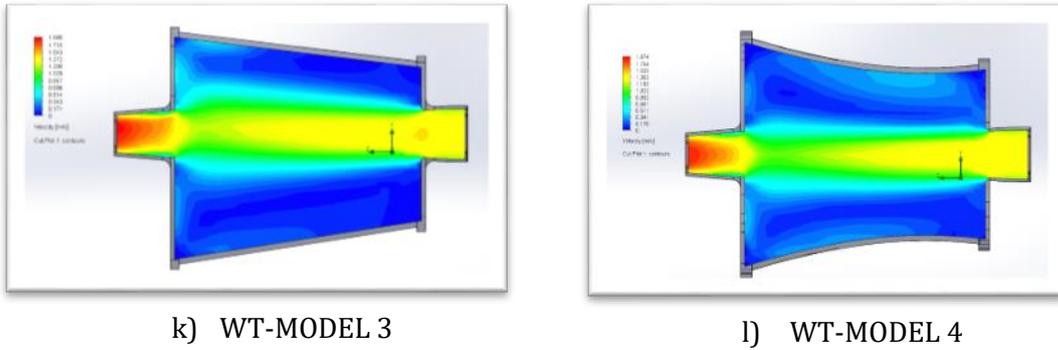


Fig 4 Velocity Contour Distribution

3.3 The Relationship Between the Data Outlet Velocity and The Contour Velocity Distribution in Spacer

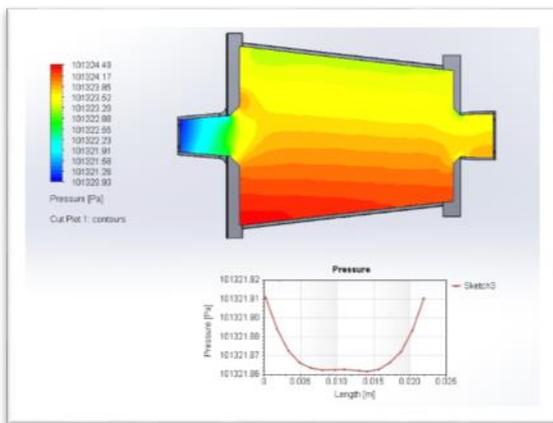
The outlet velocity analysis of the four spacer models reveals that although their average velocities are nearly identical, their flow characteristics differ significantly. WT-MODEL 1 demonstrates stable flow with only minor turbulence near the edges, while WT-MODEL 2 shows a strong central jet that enhances direct flow but may cause localized high velocities. WT-MODEL 3 performs the weakest, as its turbulent and uneven gradients reduce airflow efficiency and increase the likelihood of deposition losses. In contrast, WT-MODEL 4 provides the smoothest and most uniform velocity distribution, despite having the widest velocity range. The close match between its average and bulk average values further highlights its aerodynamic stability. Therefore, WT-MODEL 4 can be considered the most effective design, offering balanced airflow that supports consistent and efficient aerosol delivery.

3.4 The Pressure Analysis Outlet

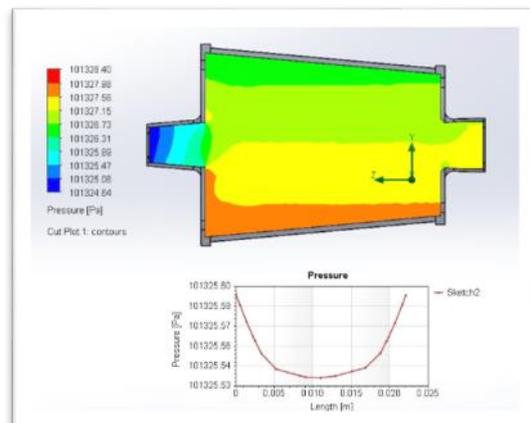
Pressure analysis at the nozzle outlet was performed to better understand the fluid behavior within each spacer design. The pressure gradient is the main driving force that governs airflow acceleration and particle transport.

Table 2 Pressure Outlet

WT-MODEL	Minimum Pa	Maximum Pa	Average Pa	Bulk Average Pa
1	101320.93	101321.17	101321.05	101321.05
2	101324.64	101324.87	101324.75	101324.75
3	101324.76	101325	101324.88	101324.88
4	101324.71	101324.96	101324.84	101324.84



a) WT-MODEL 1



b) WT-MODEL 2

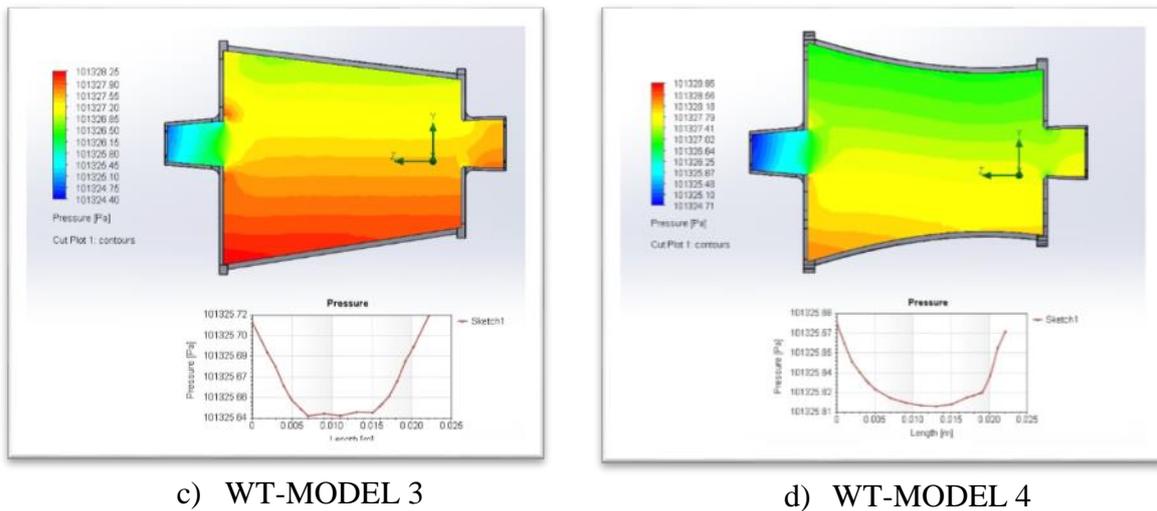
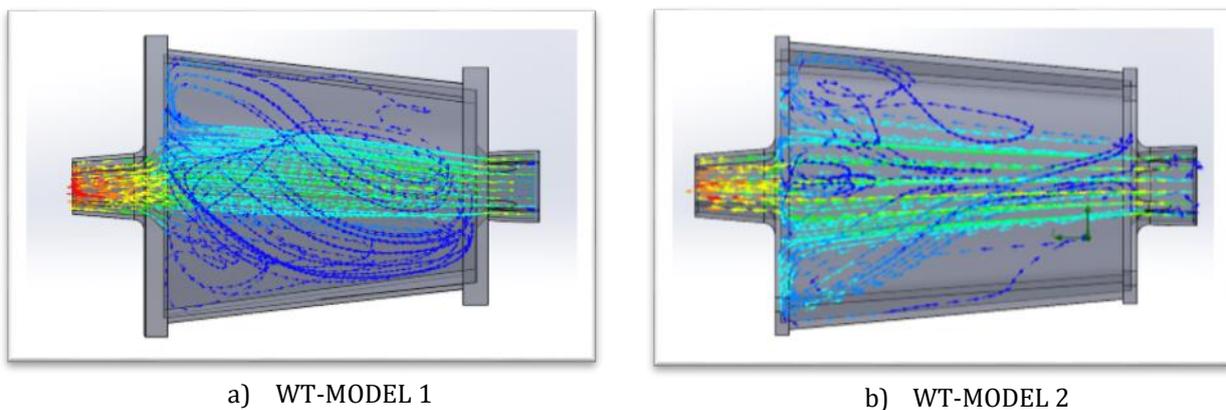


Fig 5 Pressure Distribution

Outlet pressure distribution results from (Table 2) showed WT-MODEL 1 with the lowest average pressure of 101321.05 Pa (range: 101320.93–101321.17 Pa), slightly below atmospheric levels, indicating small drops from turbulence. WT-MODEL 2 recorded an average of 101324.75 Pa (101324.64–101324.87 Pa), with stable distribution and minimal variation. WT-MODEL 3 achieved the highest and most stable pressure of 101324.88 Pa (101324.76–101325.00 Pa), nearly identical to atmospheric conditions, though velocity contours still showed turbulence. WT-MODEL 4 maintained similarly stable pressures with an average of 101324.84 Pa (101324.71–101324.96 Pa), while also providing the smoothest velocity distribution. Overall, WT-MODEL 4 offered the best aerodynamic performance by combining stable outlet pressure with uniform velocity flow, outperforming WT-MODEL 1 (pressure drop), WT-MODEL 2 (centralized but stable flow), and WT-MODEL 3 (stable pressure but turbulent velocity).

3.5 Flow Trajectories For Velocity In Each Spacer

Streamline analysis showed that WT-MODEL 1 had steady and smooth trajectories, supported by a narrow velocity range of 0.980–1.816 m/s, indicating efficient flow with only minor turbulence at the outlet margins. WT-MODEL 2 produced a strong centralized jet with higher variation (0.727–1.880 m/s), suggesting well-directed core flow but reduced uniformity across the outlet. WT-MODEL 3 exhibited irregular trajectories and turbulence, reflected in its broad range of 0.743–1.886 m/s, leading to less effective aerosol transfer. In contrast, WT-MODEL 4 achieved the smoothest and most balanced trajectories, with uniform flow direction and efficient mixing, despite a wider velocity range of 0.361–1.874 m/s. Furthermore, WT-MODEL 4 provided the most stable and uniform outlet flow, whereas WT-MODEL 3 showed the weakest performance due to turbulence and irregular velocity patterns.



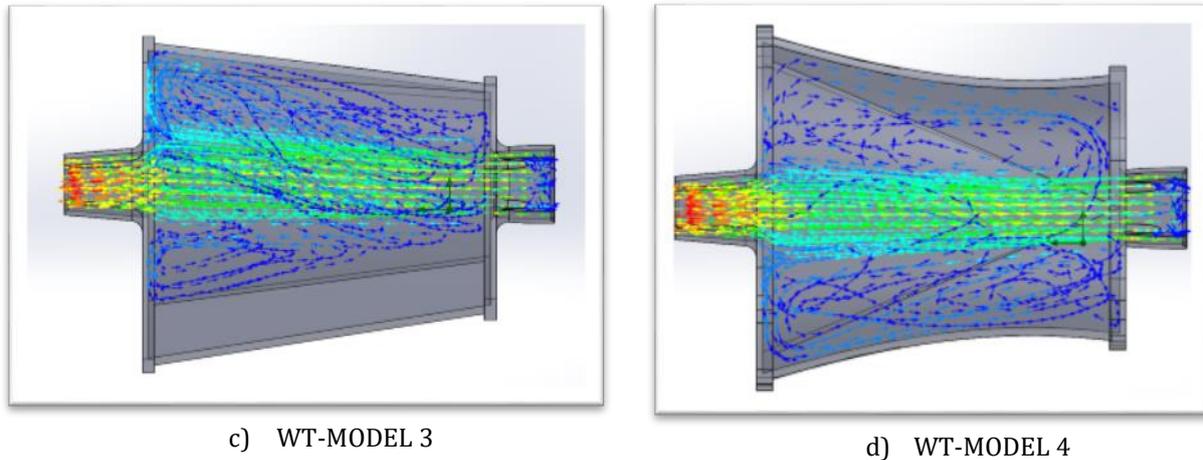


Fig 6 Flow Trajectories of Each Spacer

4.0 Conclusion

A steady outlet pressure that was similar to the atmospheric ideal was also demonstrated by WT-Model 4 for optimal aerodynamic performance and effective drug distribution. These features showed that there were few energy losses and that airflow moved through the spacer smoothly. The efficiency and uniformity of aerosol distribution to the patient were enhanced by consistent outlet velocity and stable pressure at the output, which decreased turbulence and deposition inside the spacer.

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Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

*All authors confirm their contribution to the paper as follows: **study conception and design, data collection, analysis and interpretation of results, draft manuscript preparation.** All authors reviewed the results and approved the final version of the manuscript.*

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