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CFD Analysis of the Influence of Tank Geometry on Laminar Flow Stability in Continuous Latex Dipping Processes

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1 Introduction

The latex dipping technology plays an important role in production of medical devices such as surgical gloves where thin and uniform film coating is very important [1]. The properties of the final dipped products are highly dependent on the hydrodynamic conditions within the latex dipping tank. Flow behaviour of the latex within the dipping region directly affects to the coating uniformity, film thickness and mechanical properties of the final product [2]. Therefore, the study of the flow patterns in dipping tanks becomes a matter of both scientific and industrial importance.

Even though the tank hydrodynamic is very important for the latex dipping industry, number of research which focused on the role of tank geometry in controlling flow characteristics is very limited. Most of the studies emphasize the latex formation and dipping parameters [3], but the effect of the tank shape on achieving required laminar flow in the dipping region remains unexplored. Variation in tank design specially in the mixing region can alter velocity distribution, turbulence levels, and particle suspension, which directly affects to the process efficiency and product quality. This gap highlights the requirement of systematic evaluation of flow dynamics in latex dipping tanks with different geometrical configurations.

This study investigates the influence of the shape of the mixing area of the dipping tank on flow behaviour using computational fluid dynamics (CFD) simulations. Three tank geometries were analysed and compared with respect to visual flow pattern, cell Reynolds number and turbulent kinetic energy in the former moving direction after dipping and the velocity magnitude in the perpendicular direction. The objective of this study is to identify the configuration which provide a stable laminar flow, minimizing disturbances and ensuing uniform coating condition. The findings aim to provide insight into the optimization of latex dipping systems mainly supporting laboratory-scale applications.

2 Experimental Section

2.1 Simulation Overview

Computational fluid dynamics (CFD) simulations were conducted using ANSYS Fluent (version 2021 R2) to analyse the variation of internal flow characteristics of latex dipping tank with different tank geometries. Three different tank shapes, Shape A, Shape B, and Shape C shown in the **Figure 1** were modelled in Solidworks and simulated in ANSYS and compared to evaluate their effect on flow uniformity and laminar stability.

Tank width, length, height and the dimensions of the dipping region is similar for all three designs, with only difference being the shape of the tank at the latex mixing region of the tank. An axial impeller would be assembled in this area allowing latex mixing minimizing sedimentation and guiding latex along the dipping region of the tank.

2.2 Geometry and Model Setup

All the tank models were designed in SolidWorks 2022 with the former moving direction after dipping was oriented along the X-axis while the tank base is on the XZ-plane. All three tanks were modelled with almost same volume capacities of approximately 0.9 m^3 to maintain comparable flow conditions. The dipping region was modelled as a 0.8 m × 0.6 m rectangular zone, representing the typical area through which the former moves. For all three tank geometries the impeller rotational speed was used as the 50 rad/s.

2.3 Mesh Generation

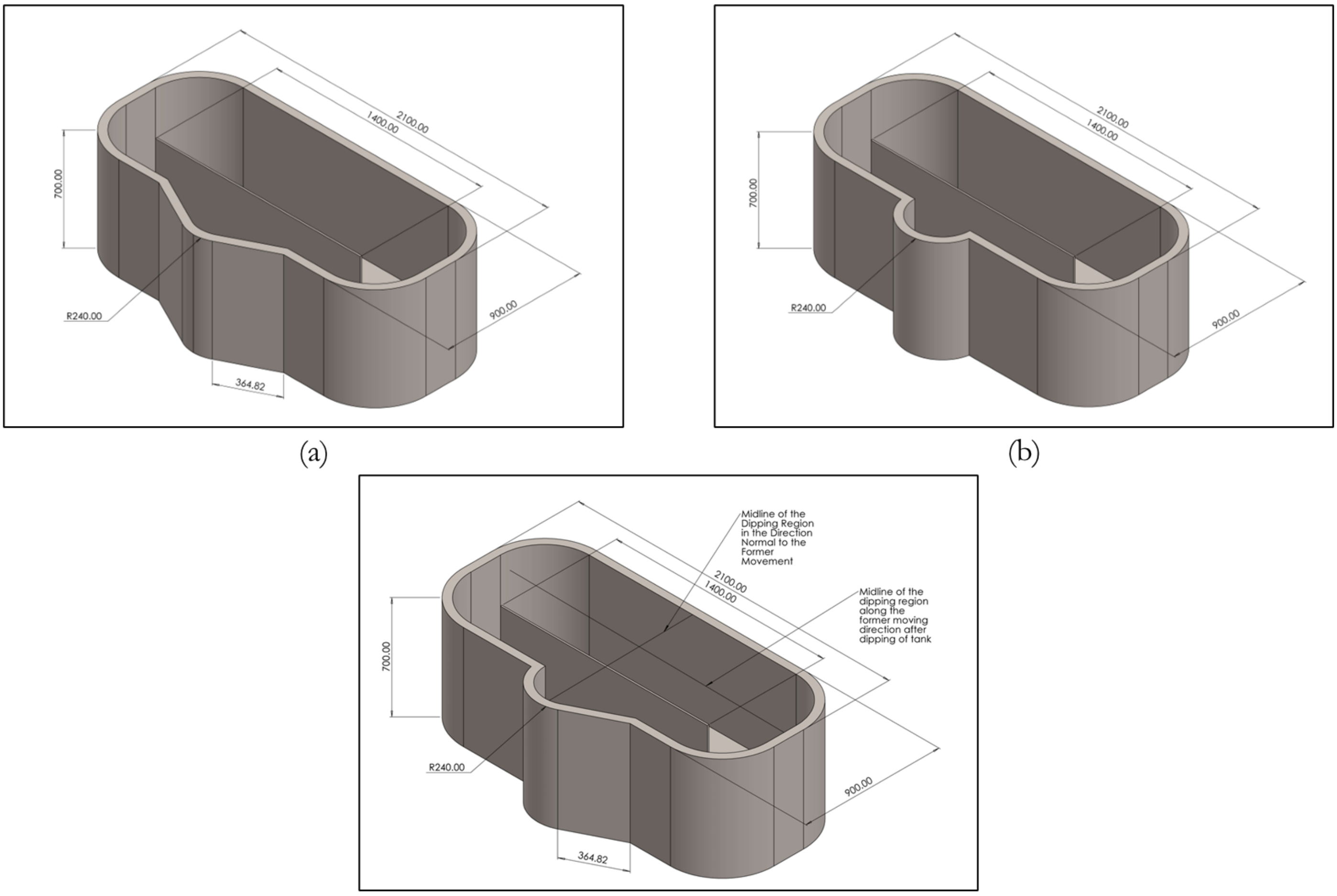
A structured mesh was generated for each geometry using ANSYS Meshing. Mesh refinement was applied near the corners and the wall of the tank. The total element counts ranges from 102135 to 219649.

2.4 Fluid Properties

The working fluid was modelled as latex, approximately as a Newtonian fluid with following properties.

Density = 920 kg/m^3

Specific heat capacity (Cp) = 1880 J/kg.K



(a)

(b)

(c)

Figure 1. SolidWorks-modelled CAD Designs of (a) Tank Shape A, (b) Tank Shape B, and (c) Tank Shape C, Imported to ANSYS as STEP Files

Thermal conductivity = 0.13 W/m.K

Viscosity ` = 0.02 Pa.s

In a few studies, rubber latex has been recorded to show behaviour that is Newtonian in nature at low shears, despite exhibiting some non-Newtonian character at high shears. The operating conditions of latex dipping tank (impeller speed of 50 – 150 rpm, impeller diameter of 0.20 – 0.40 m) give average shear rates of 1 – 3 s^{-1}, which is within a Newtonian shear region. Experimental rheological studies indicate that, at such low strain low frequency conditions, latex will behave such that, shear stress is proportional to shear rate and viscosity is a constant which is essentially what behaves Newtonian [4]. Since the hydrodynamic conditions of the dipping process are within such region, the latex can be modelled as a Newtonian fluid with enough plausibility for purposes of analysing flow and mixing in this study. The shear strain rate value along the dipping region of tank shape C is shown in the **Figure 2**. The temperature was neglected under isothermal conditions at room temperature (298 K).

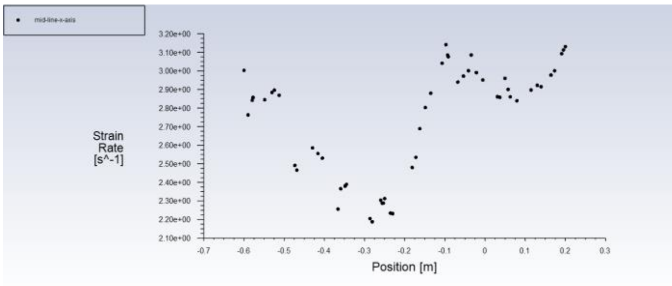


Figure 2. Shear Strain Rate Values along the Dipping Region of Tank Shape C

2.5 Solver Settings

A pressure-based steady solver was employed for the simulations with the SIMPLE scheme for pressure-velocity coupling. Spatial discretization used second-order accuracy, and convergence was assumed when the residuals for continuity and momentum equations dropped below 0.001.

2.6 Evaluation Parameters

The comparison of flow performance of each geometry was conducted using following four key parameters.

1. Visual flow pattern, which represents the qualitative visualization of streamline distribution and vortex formation.
2. Cell Reynolds number along the former moving direction, which assess flow regime stability.
3. Turbulent kinetic energy along the dipping axis, which quantify the turbulence intensity.
4. Velocity magnitude in the direction perpendicular to the former moving direction, to evaluate lateral uniformity of the latex flow in the dipping region.

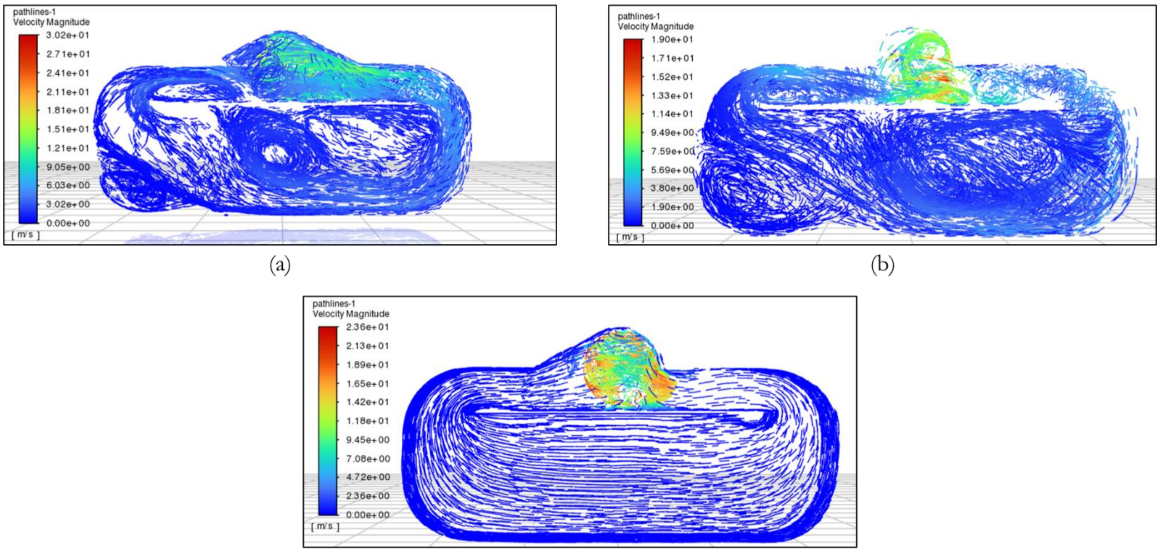
3 Results and Discussion

The results obtained from ANSYS Fluent simulations were compared using above mentioned evaluation parameters. These parameters were selected to identify how the geometry of the latex dipping tank affects to the transition between laminar and turbulent flow regime, which directly affects to the quality of the final product. In continuous production of latex dipping products, smooth and stable laminar flow along the former moving direction after dipping is required to ensure even coating thickness and minimize surface defects on the dipped products.

3.1 Visual Flow Pattern

The visualization of fluid flow pattern inside the tank provides an important qualitative understanding of how the fluid circulation within the tank happens and how effectively mixing and uniformity are achieved. The regions of recirculation, stagnation or excessive turbulence, which indicate how well the fluid motion supports laminar suspension can be identified by comparing the visual flow pattern among the tank geometries. Studying the streamline behaviour also helps to locate the potential dead zones where particle settling may occur.

The **Figure 3**, illustrate the visual flow pattern of the tank shape A, B, and C. For tank shape A simulation results shows strong recirculation zones in both mixing and dipping regions, which are accompanied by multiple intersecting flow loops. These irregular and multidirectional path lines prove the presence of turbulence and mixing inside the tank.



(a) (b)

(c)

Figure 3. Visualized Fluid Flow Patterns for (a) Tank Shapes A, (b) Tank Shape B, and (c) Tank Shape C, Showing Circulation Behaviour, Mixing Uniformity, and Regions of Recirculation, Stagnation, or Potential Dead Zones

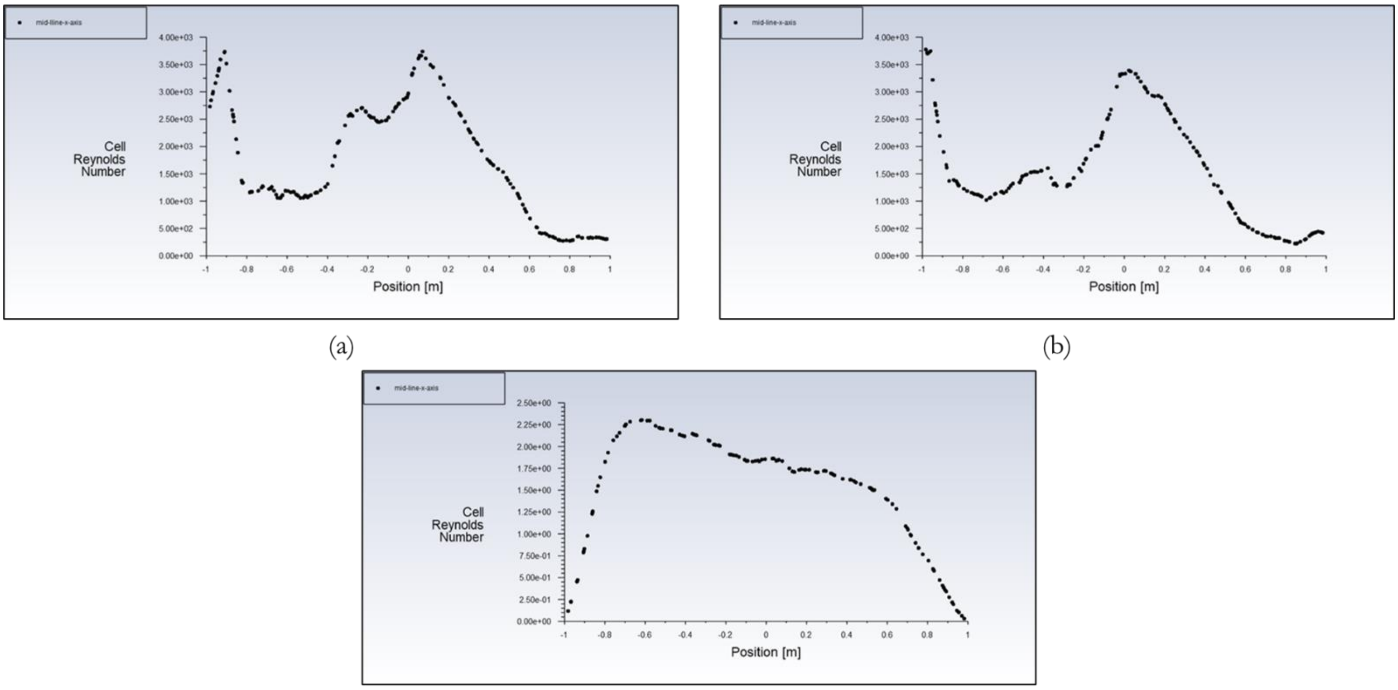
The path lines obtained through simulation for tank shape B also shows an unsteady flow pattern. They are characterised by several overlapping eddies and curved path lines, indicating continuous flow redirection within the tank. Particle entrapment and non-uniform latex concentration can be expected by those non-uniform velocity contours and strong circulation in the dipping region.

In contrast, simulation results of tank shape C show more organised streamlines flow structure in the dipping region. A transition towards laminar behaviour is indicated by those smoother and predominantly aligned path lines along the intended dipping tank direction. The absence of chaotic vortices and the well-defined recirculating zone suggest a stable flow regime, which support continuous dipping and reduce sedimentation.

3.2 Cell Reynolds Number

The cell Reynolds number in ANSYS Fluent solution indicates a localised measure of the flow regime within each control volume of the computational domain. The conventional Reynolds number represent the average flow characteristics based on bulk velocity and a single characteristic length, while the cell Reynolds number is calculated individually for every mesh cell using its local velocity magnitude and representative cell domain. Therefore, this parameter provides measurement of how the flow behaves at a microscopic scale. Regions with possible flow transitions or instabilities along the former moving direction after dipping can be identified by analysing the distribution of cell Reynolds number along the former moving direction after dipping. Consistently low cell Reynolds number indicates stable laminar flow, and localised increases suggest areas where flow separation or turbulence may arise.

Figure 4 illustrate the cell Reynolds number along the midline of the dipping region along the former moving direction after dipping of tank shape A, shape B, and shape C. The general threshold Reynolds value between laminar and turbulent flow lies between 2300. Values lower than this indicates smooth laminar flow, while higher values indicate transition or turbulence.



(a) (b)

(c)

Figure 4. Cell Reynolds Number Distribution along the Midline of the Dipping Region in the Former's Moving Direction for (a) Tank Shapes A, (b) Tank Shape B, and (c) Tank Shape C

For tank shape A, the cell Reynolds number fluctuates between approximately between 5×10^2 and 4×10^3, indicating strong velocity gradients and the presence of turbulence-inducing vortices.

Tank shape B also shows a similar pattern to the tank shape A with Reynolds number reaching up 3.8×10^3. Even though the magnitude and trend closely similar to tank shape A, the fluctuations in shape B are slightly smoother. This suggests a marginally more stabilised flow field but still lies within the turbulent regime.

Conversely, cell Reynolds number across the entire length in tank shape C remains below 2.5, confirming that the flow is fully laminar without any local disturbances or large velocity gradients which can trigger turbulence.

3.3 Turbulent Kinetic Energy

Turbulent Kinetic Energy (k) represent the mean kinetic energy per unit mass associated with the velocity fluctuation in a turbulent flow region. This parameter helps to quantify the intensity and distribution of turbulence within a fluid domain. In this study, to evaluate the degree of flow stability across the tank geometries, k was obtained along the midline of the former moving direction after dipping. The expression for k is given by,

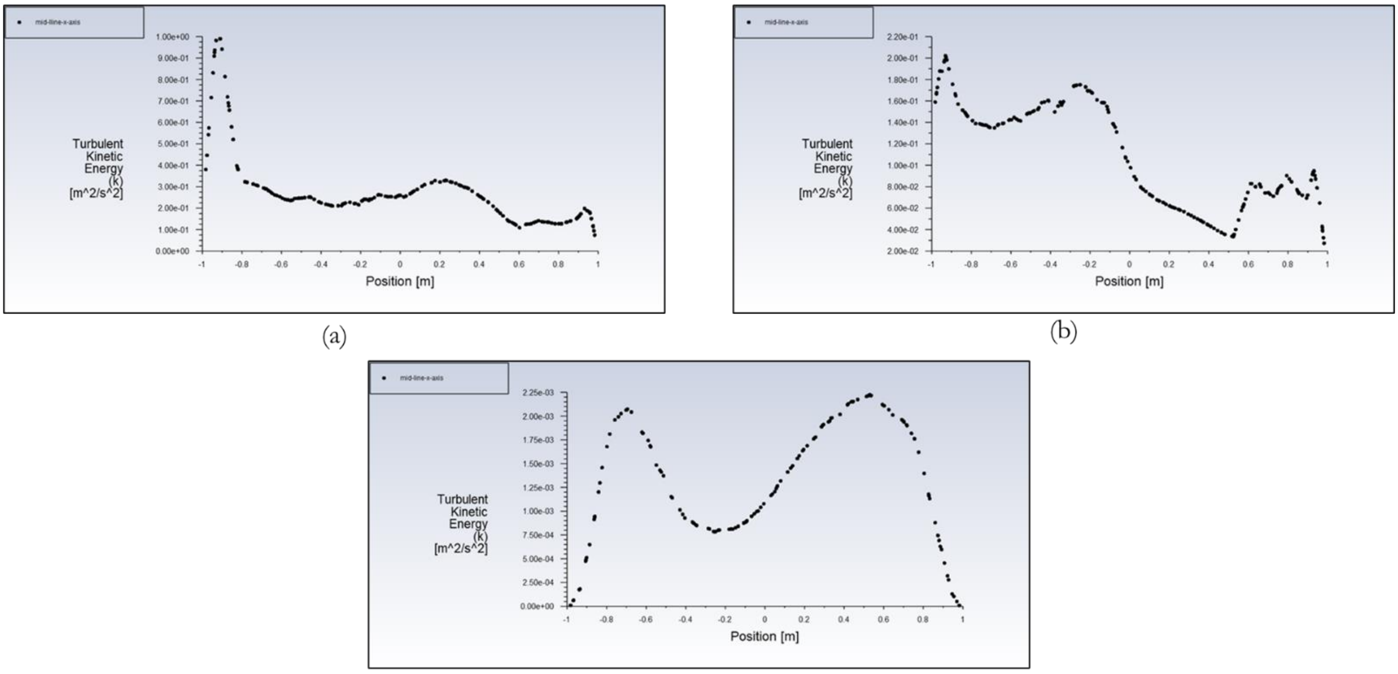
$$k = \frac{1}{2}(u'^2 + v'^2 + w'^2) \qquad \text{Eq. (2)}$$

where u', v', and w' denote the velocity fluctuation in the three coordinate directions.

Higher k values indicate higher turbulence and energy dissipation, which can lead to unsteady flow, while lower k values indicate the laminar flow conditions with minimal fluctuations.

The **Figure 5** illustrate the variation of turbulent kinetic energy (k) along the midline of the former moving direction after dipping for the three tank geometries of tank shape A, shape B, and shape C.

In tank shape A, the turbulent kinetic energy is the highest reaching values close to 1.0 m^2/s^2, indicating strong velocity fluctuations and significant energy dissipation. It suggests the presence of intense turbulence zones.



(a)

(b)

(c)

Figure 5. Variation of Turbulent Kinetic Energy (k) along the Midline in the Former Moving Direction after Dipping for (a) Tank Shapes A, (b) Tank Shape B, and (c) Tank Shape C

The profile of tank shape B shows multiple small fluctuations along the former moving direction after dipping, suggesting localised eddy formations and partially stabilized flow with moderate level of turbulence, peak k values around 0.2 m^2/s^2. The turbulence intensity of tank shape B is lower than tank shape A, but sufficiently higher disturbances to the uniform flow is expected.

Tank shape C shows a markedly different behaviour than other two tank geometries as the turbulent kinetic energy remains very low on the order of 10^{-3} m^2/s^2 throughout the length of the tank. This indicates that the velocity fluctuations along the former moving direction after dipping are minimal, and the flow remains largely laminar. The absence of sharp peaks also confirms that the flow is smooth and stable.

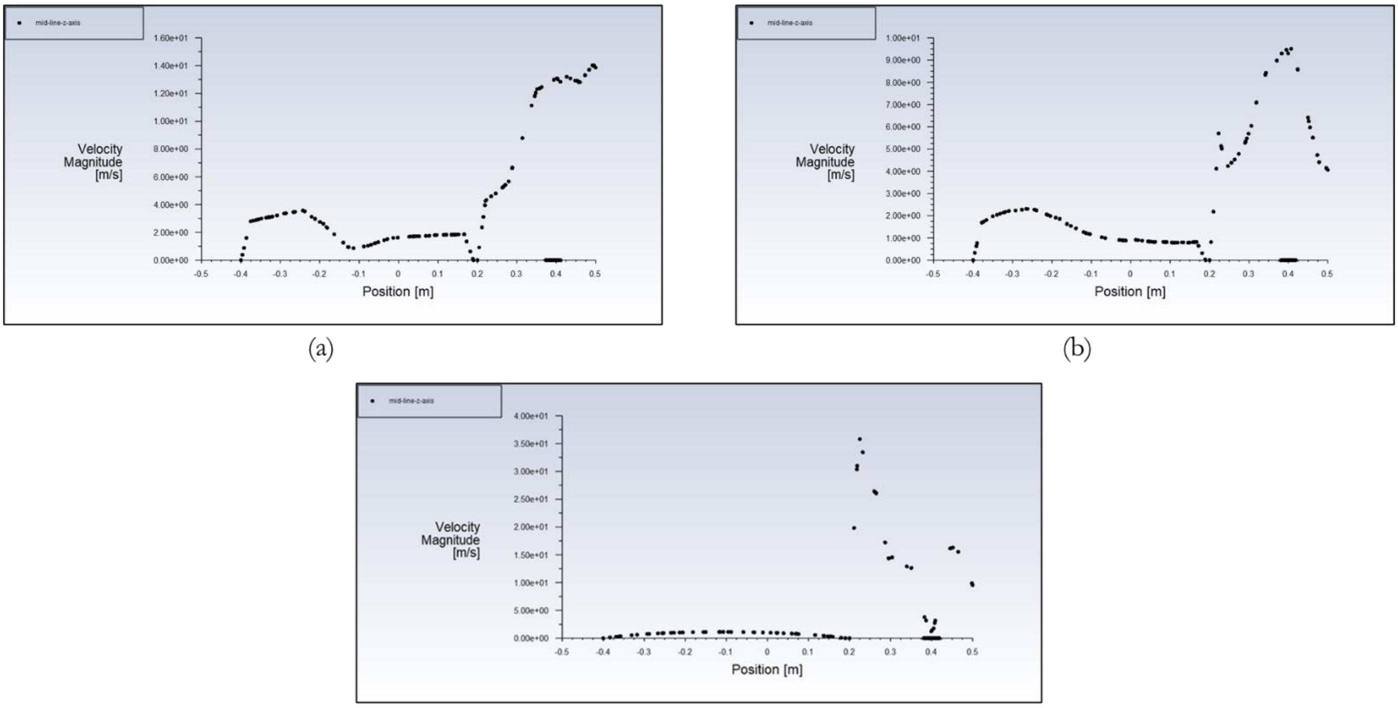
3.4 Velocity Magnitude

The degree of lateral flow disturbance within each tank geometry were evaluated by analysing the velocity magnitude in the direction perpendicular to the former dipping path. Any fluid motion deviates from the desired former moving direction after dipping can be identified through this parameter. This scenario can influence the uniformity of latex distribution during coating. In an ideal laminar flow, this parameter value should remain minimal along the perpendicular direction to the former moving direction after dipping, signifying smooth and stable motion of fluid layers. In contrast, higher variation in perpendicular velocity magnitude indicates lateral mixing and unsteady flow behaviour.

The **Figure 6** shows the variation of velocity magnitude along the midline of the dipping region in normal direction to the former moving direction after dipping. Position -0.5 m to 0.2 m represents the dipping region and from 0.2 m to 0.5 m represents the mixing region.

In tank shape A, there are irregular variations of the velocity magnitude along the Z-axis, indicating the presence of strong lateral flow components and localised vortices which are typical characteristics of turbulent flow. The fluid motion within the dipping region is not well-aligned along the former moving direction after dipping, implying unstable circulation zones and secondary flow patterns within the dipping region.

Tank shape B demonstrates a similar noticeable fluctuation but slightly smoother pattern than tank shape A. The overall magnitudes are somewhat lower, but the data still exhibit distinct variations along the Z-axis. This signifies that the flow is still far from being purely laminar also in tank shape B with partial cross-directional disturbances.



(a) (b)

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Figure 6. Variation of Velocity Magnitude along the Midline of the Dipping Region in the Direction Normal to the Former Movement for (a) Tank Shape A, (b) Tank Shape B, and (c) Tank Shape C.

In contrast, tank shape C displays a remarkably stable velocity profile along the Z-axis. The values are nearly constant and minimal throughout the entire dipping region without sharp fluctuations, confirming absence of significant flow in the perpendicular direction. therefore, the fluid motion is well-confined along the main dipping axis. This behaviour indicates laminar flow with smooth, uniform fluid movement.

4 Conclusions

The numerical study investigated the influence of the shape of the mixing area on the internal flow characteristics of latex dipping tank, with the objective of achieving a smooth and stable laminar flow pattern in the dipping region required for continuous dipping operations. Based on the simulation results of velocity magnitude, Cell Reynolds number, visual flow pattern, and turbulent kinetic energy distribution, it was observed that the only tank shape C configuration exhibited an acceptable laminar flow along the former moving direction after dipping. the velocity components in the perpendicular direction within the dipping region in this configuration are negligible. In contrast, tank shapes A and B geometries demonstrated higher turbulence levels, evident from elevated Reynolds numbers and irregular velocity fluctuations. This could lead to non-uniform coating and surface defects. Therefore, the optimised tank shape C design provides improved flow uniformity and minimizes sedimentation effects, ensuring consistent product quality in latex dipping applications.

Declaration of Competing Interest

The authors declare no competing interests.

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