Numerical Simulation of Flow past Glove-shaped Formers in Latex Dipping to Consider Tip Effect to Free Surface Flow

W Koranuntachai1,2, T Chantrasmi1,2 and U Nontakaew1,2

1Development of Machinery and Industrial Equipment Research Center (DMIE), King Mongkut’s University of Technology North Bangkok, 1518 Pracharat1 Road, Wongsawang, Bangsue, Bangkok 10800 Thailand.
2Department of Mechanical & Aerospace Engineering, Faculty of Engineering, King Mongkut’s University of Technology North Bangkok, 1518 Pracharat1 Road, Wongsawang, Bangsue, Bangkok 10800 Thailand.

Abstract
Latex-dipping process in a medical-gloves production line is one of the most critical components that affect the final product quality. In this process, glove-shaped formers are moved through an open-channel latex-dipping tank. Since the gloves have long arms and the latex compound is opaque, it is difficult or impossible to directly observe the flow beneath the free surface. On the other hand, the surface wave and vortex shedding patterns are easily observed or measured on-site. Therefore, it will be beneficial to identify and establish a relationship between the observable surface quantities and the flow underneath. In this work, Computational Fluid Dynamics (CFD) is used to simulate a free-surface flow past a glove-shaped former in comparison to that over a vertical cylinder of the same diameter. The computational results showed that the vortex generation in the near wake is inhibited by the effect of the free surface, and reducing the vortex shedding and vorticity. The shedding from the fingertips has little to no effect on the surface. Most surprisingly, the free surface flow past a glove-shaped former in this setting does not exhibit a transient vortex-shedding pattern unlike the case with a vertical cylinder. This disparity among others makes a vertical cylinder a poor simplified surrogate model for the glove-shaped former.

Keywords: Latex Dipping, Free-Surface Flow, Computational Fluid Dynamics

1. Introduction
In a production line of the rubber medical gloves, the final products are the solid elastic gloves made from the liquid latex compound. In a continuous production line, the long conveyor chain carries an array of glove-shaped ceramic formers (molds) through a variety of processes such as former cleaning, former drying, coagulant dipping, latex dipping, gelling, vulcanizing, beading, and stripping [1–3]. One of the most important processes is the latex dipping (see Figure 1), the formers are dipped into latex compound in the latex dipping tank to create the thin coating layer of latex film around the formers through a chemical process called “Latex Film Formation” [4]. This liquid film would then be turned into rubber medical gloves in a later process.
During the latex dipping process, the formers are lowered into a flow of latex compound. Usually, there is one dipping tank on each side of the conveyor chain. Each tank usually has a slow-rotating propeller to drive the latex compound in a loop circulation with one long straight section into which the formers will be lowered. The latex compound flow is generally in the same direction as the movement of the formers. In this way, the relative velocity between the formers and the fluid is reduced. This is believed to improve the quality of the products and reduce the number of rejects.

Final product quality and rejection rate are affected by several fluid flow phenomena that could occur in the straight dipping section of a latex dipping tank. Certain realistic combinations of the properties of latex compound, geometrical dimensions, and the conveyor chain speed might result in turbulent flow in the tank. On the other hand, some other combinations might result in vortex shedding from the flow past an array of formers. Note that the driving propeller can control the speed of the latex flow. However, the turbulent channel flow happens due to high relative velocity between the latex and the stationary tank walls, while the vortex shedding is dependent on the relative velocity between the latex and the moving formers. Since the formers move at the conveyor speed, which in turn dictates the production rate of a continuous manufacturing line, it is not an easy problem to predict and optimize the latex dipping process.

![Image](image-url)

**Figure 1.** Latex dipping process in a continuous production line

Even with an operating latex-gloves production line, the flow phenomena are difficult to observe due to the latex compound being opaque. In practice, only the free surface can be easily observed. Thus, this work is an attempt towards understanding the behaviors of the fluid flow in the latex dipping tank with an emphasis on observable free surface flow.

Historically, the free surface analysis was used to study the surface wave influencing the offshore structures (such as an oil drill). In the old days, this was done by using the mathematical theory [5–7]. In recent years, computational power and simulation software has been developed to be powerful enough to simulate such problems with more accuracy via numerical methods. In particular, Computational Fluid Dynamics (CFD) simulations are frequently employed to model complex multi-physics problems. Flow simulation with interfaces and free surface flows are more of a prevalent topic [8,9]. In many works, vertical cylinders were used as a representative solid structure within the free surface flow [10–12]. The transient free surface can clearly be shown and monitored [13,14].

This work presents CFD simulation of the free surface flow past one latex-gloves former. A similar flow past a vertical cylinder of the same diameter as the former was also carried out as a comparison reference. Note that flow in a real latex dipping tank will be more complicated due to its being a flow past an array of formers instead of a single one. Nonetheless, the present work can serve as a basis of understandings of the real flow. It will also answer the question of whether it is reasonable to estimate the geometry of a former with that of a cylinder.
This paper is divided into five sections, including this one. The next section formulates the model problems and describes the case studies. The numerical setup is described in the third section. The simulation results are presented and analyzed in the following section. Lastly, the conclusions are made in the final section.

2. Model problem

Figure 2 shows a simplified drawing of a latex dipping tank unit. It is designed for both sides of the conveyor chain (so only one unit is needed for one production line). On each side of the conveyor chain, an array of formers will be moving lengthwise in a single file. This type of former array configuration is generally called “single-former.”

Figure 2. An example of a simple latex dipping tank design

The conveyor speed ($U$) and the dwell time (dipping time) are the main variables that determine the length of the latex dipping channel ($L_c$). In general, faster conveyor speed is desired for a higher production rate. A latex-dipping tank must be designed accordingly to work suitably at such a high speed, and the dwell time is the parameter that is directly related to the thickness of the rubber gloves, the dwell time between 8-12 seconds is generally enough to pass the rigorous testing requirements of the industry standards [15–16].

Conveyor speed of 0.35 m/s, which is typical of this type of production line, is used in this work. The latex-dipping channel is 40 cm wide, and the latex height is 50 cm from the channel bottom. The pressure gradient is calculated to be approximately 1.0 Pa/m.

Three material properties of the latex compound are needed for the analysis in this work: density ($\rho$), viscosity ($\mu$) and surface tension ($\sigma_s$). Their values depend on the compound formula. In this work, nominal values of 1,000 kg/m$^3$, 200 cP and 44.2 mN/m are used, respectively. Note that the fluid is assumed to be Newtonian for the sake of simplicity. The air above the free surface is assumed to be at 25°C and 1 atm.

For this work/paper, the former landing and departing regions are not considered and the flow is approximately as fully developed away from these regions. Figure 3(a) shows a schematic diagram of the simplified model problem and the flow direction. (Note that this is a positive flow direction. In certain scenarios, the latex compound can flow the other way in some regions.) As such, the left boundary will be called an inlet and the right boundary will be called an outlet.

3. Numerical setup

This section describes the second step in the proposed analysis. The CFD simulations based on the Finite Volume Method [17–20] were performed. The commercial software ANSYS Fluent was used. The Volume of Fluid (VOF) model [18] was selected for solving the interaction between two fluid phases. Only one former was drawn in the domain. The side and bottom walls were set as moving walls (with constant velocity) relative to the stationary former. The latex flow was expected to be laminar (possibly with laminar vortex shedding) at this Re of 122.
Two cases were simulated in this work (1) latex dipping flow past a vertical cylinder, and (2) latex dipping flow past a glove-shaped former. The diameter of the former’s forearm and that of the cylinder are the same. The length of the former resembles the actual piece (3D-scanned CAD was performed from a real former) while the vertical cylinder spans the entire depth of the fluid domain.

Figure 4 shows the mesh for the first case (cylinder). The mesh is refined near the former surface as well as the interface between the two fluids (latex compound and air) in order to capture potential vortex shedding and the free surface accurately. The hexahedron mesh is used for the computational domain and the total number of cells is around 440,000 cells.

Figure 5 shows the mesh for the second case (glove-shaped former). The meshing method far from the former is similar to the first case. However, the meshing of a latex-gloves former is much more difficult due to the complex shape of the former (and the tolerance of the 3D scan in the CAD file). Once again, the hexahedron mesh is used and the total number of cells is around 1,046,000 cells.
Figure 5. Detailed sections of the computational mesh for free surface flow past a glove-shaped former in a latex dipping tank

The main driving force for the flow comes from the propeller installed as part of the dipping tank. It creates the driving pressure difference which can be simplified to pressure gradient, \( \frac{\partial P}{\partial x} = -\frac{\Delta P}{L_x} \) since it is assumed that the flow in this section is fully developed. When the moving frame of reference (fixed former) is considered, the velocity profile at the inlet is then:

\[
 u_{rel}(y,z) = U - u(y,z)
\]

The fully developed velocity profile \( u(y,z) \) of an open channel flow can be obtained by solving a Poisson’s equation with appropriate boundary conditions (three zero Dirichlet boundaries and one zero Neumann boundaries).

\[
 \nabla^2 u = \frac{1}{\mu} \frac{\partial P}{\partial x}
\]

The fully developed velocity profile \( u(y,z) \) of an open channel flow for latex compound can be obtained by solving a Poisson’s equation with appropriate boundary conditions (three zero Dirichlet boundaries and one zero Neumann boundaries). The gauge pressure at the liquid inlet is set as \(-L_x \frac{\partial P}{\partial x}\). As for the air, the uniform velocity equal to the conveyor speed is used at the inlet with atmospheric pressure. No-slip boundary conditions were applied to the surface of the cylinder and former. The side and bottom boundaries are set as moving wall with (negative) conveyor speed, while the pressure outlet boundary conditions are all set to atmospheric (zero gauge pressure).

4. Results and discussion

It turned out that the flow over a vertical cylinder exhibits laminar vortex shedding as could be theoretically predicted at this Reynolds number, \( \text{Re}_D = 122 \) (without considering the free surface and wall effects). Surprisingly, however, the flow over a glove-shaped former was steady without the transient vortex shedding. It would seem that the two flows were in different flow regimes and thus many quantitative comparisons would be quite meaningless. Nevertheless, the authors expect that when an array of formers are considered in a future, laminar vortex shedding in a more complex fashion would be present as observed from an actual latex dipping tank. Thus, in this work, the two cases were compared as if they both had transient laminar vortex shedding.
The measures for comparison of the two cases were (4.1) free surface visualization, (4.2) velocity field in the middle vertical plane, (4.3) vertical vorticity field at various depths, (4.4) free surface elevation vs. streamwise coordinate, and (4.5) Strouhal number and maximum sideways lift coefficient. For the first three measures, instantaneous fields will be shown. The details of the comparison are as follows.

41. Free surface visualization
Figure 6 shows the instantaneous free surface visualization of the two cases. Since the VOF method uses a continuous volume fraction field as a way to keep track of the interface between the two fluids, the volume fraction of 0.5 was selected as isosurface value to render this free surface. In the case of flow past a vertical cylinder, the wave profile exhibits a bow wave pattern in front of the cylinder and a clear vortex-shedding pattern in the wake region. In the case of flow past a glove-shaped former, bow wave pattern in the front and steady circulation regions in the wake region could be observed but the elevation levels were much less pronounced.

4.2 Velocity field in the middle vertical plane
Figure 7 shows interior flow structures in the fluid domain by way of velocity vector plots in the middle vertical plane. In case of the flow past a vertical cylinder, a vortex-shedding pattern can be seen all the way down to the tank bottom. It could also be observed that the pattern was less pronounced near the free surface due to the surface tension and air resistance. In case of the flow past the former, a large single recirculation region was formed. In this view, the recirculation region appeared as a triangle with the last fingertip as one vertex. No other visible flow structure could be observed.

![Flow past a vertical cylinder and a glove-shaped former](image)

**Figure 6.** The instantaneous free surface of the two cases
Figure 7. The velocity field in the middle vertical plane of the two cases

4.3 Vertical vorticity field at various depths

Figures 8 and 9 show instantaneous vertical vorticity (rotation around z-axis) magnitude at four depth levels – (a) the original interface level, (b) 5 mm. deep, (c) 200 mm. deep and (d) 300 mm. deep – of the flow past a cylinder and that past a former, respectively. In the first case, Kármán vortex street pattern can be observed, especially near the interface level. At the lower depth levels, it could still be seen but the vortices dissipated much more quickly downstream.

In case of the flow past a glove-shaped former, asymmetric twin vortices were formed likely due to the asymmetry in the hand section of the former. At the interface level, the vortex strengths were much weaker than those in the first case. However, at the deeper levels, the strengths were comparable.
Figure 8. Instantaneous vertical vorticity contour in horizontal planes for flow past a vertical cylinder

(a) At the interface level  
(b) 5 mm deep  
(c) 200 mm deep  
(d) 300 mm deep

Figure 9. Vertical vorticity contour in horizontal planes for flow past a glove-shaped former

(a) At the interface level  
(b) 5 mm deep  
(c) 200 mm deep  
(d) 300 mm deep

4.4 Free surface elevation vs. Streamwise co-ordinate

A more quantitative measure of the free surface level could be visualized by taking the spatial average of the free surface elevation field across the transverse coordinate (y). Similar to the visualization of the free surface, the VOF volume fraction value of 0.5 was used to identify the surface elevation level. For the first case with vortex shedding, additional time averaging was performed. This resulted in a plot of the free surface elevation vs. streamwise coordinate as shown in Figure 10. Note that the streamwise coordinate (x) was set to zero at the center of the cylinder and the former.

It could be seen that the crest and valley of the first case were more pronounced than those of the second case. This could be directly attributed to the fact that the cylinder has more frontal area perpendicular to the free stream.
4.5 Strouhal number and maximum sideway lift coefficient

More quantitative measures for characterizing the vortex shedding were Strouhal number \((St)\) and the (maximum) sideway lift coefficient \((C_L)\). The former measure can be computed by measuring the vortex shedding frequency (e.g. by monitoring \(C_L\) over time) and non-dimensionalizing it with the conveyor speed and cylinder/former diameter. The latter measure can be calculated by measuring the total resultant force acting on the solid surface in the transverse direction \((F_y)\) then normalizing it with the dynamic pressure \(\left(\frac{1}{2} \rho U^2\right)\) times the solid body’s projected area in the xz-plane \((A)\), i.e.

\[
C_L = \frac{F_y}{\frac{1}{2} \rho U^2 A}
\] (3)

In case of the flow over a vertical cylinder, the Strouhal number was calculated to be 0.185, which was very close to the value of 0.18 from a case of 2D flow past a circular cylinder between two parallel walls with the same Reynolds number and blockage ratio [21]. The lift coefficient as a function of time oscillates symmetrically around zero with the highest magnitude of 0.518.

In case of the flow over a glove-shaped former, no transient vortex shedding occurred, therefore the Strouhal number could not be calculated. However, the flow was slightly asymmetrical due to the shape of the former, so the (steady) lift coefficient had a nonzero value of 0.017.

5. Conclusions

In this study, a three-dimensional CFD simulation with VOF technique of free surface flow representing a latex-dipping process was carried out with realistic parameters taken from an actual latex-gloves production line. The glove-shaped former was physically scanned and its geometry was used in the simulation. Another free surface flow simulation with a simple vertical cylinder of the same diameter (and the same dipping tank) was also carried out as a reference.

Many qualitative and quantitative comparisons were made between the two simulations. Notably, and quite surprisingly, the simulation case with the glove-shaped former did not exhibit a transient vortex-shedding pattern while the other case did as expected. In case of the flow past a glove-shaped former, a single circulation region was formed behind the former instead.
The free surface elevation was compared between the two cases. With a more streamlined shape and a smaller frontal area, the glove-shaped former generated less pronounced wave in front and in the wake. A quantitative calculation shows that the difference was about two times in elevation level measured from the original unperturbed baseline.

Even though the vortex structures from the forearm were less pronounced on the free surface due to air resistance and surface tension effect, they could still be visually observed from the free surface as one would inspect an actual dipping tank. The effect from fingertips could not be observed at all on the free surface as the vorticity quickly dissipated at that depth.

Due to various dissimilarities presented in this work, a vertical cylinder would be an inaccurate substitute model for the glove-shaped former. This presents some challenges in the future work when an array of formers should be considered.

References
[1] Blackley D C 1997 Polymer Latices Science and Technology Volume 3: Applications of latices (New York: Springer Science)
[2] Cacioli P 1997 Rev. Fr. d’Allergologie d’Immunologie Clin. 37(8) 1173–1176
[3] Yip E and Cacioli P 2002 J. Allergy Clin. Immunol. 110(2) S3–S14
[4] Hill D 2018 The Science and Technology of Latex Dipping (Smithers Rapra)
[5] Morison J R Johnson J W and Schaaf S A 2012 J. Pet. Technol. 2(5) 149–154
[6] Demirbilek Z and Gaston J D 1985 Ocean Eng. 12(5) 375–385
[7] Faltinsen T V O M and Newman J V 1995 J. Fluid Mech. 289 179–198
[8] Scardovelli R and Zaleski S 1999 Annual Review of Fluid Mechanics 31(1) 567–603
[9] Reichl P Hourigan K and Thompson M C 2005 J. Fluid Mech. 533 269–296
[10] Bai W and Taylor R E 2006 Appl. Ocean Res. 28(4) 247–265
[11] Kang A Lin P Lee, Y J and Zhu B 2014 Comput. Fluids 106 41–53
[12] Wu Y L 2017 Ocean Eng. 141 477–492
[13] Zhang, J Liang D Fan X and Liu H 2019 Adv. Water Resour. 123(800) 96–108
[14] Yu G Avital E J and Williams J J R 2008 J. Fluids Eng. 130(10) 101304
[15] Sasidharan K K Joseph R Rajammal G Viswanatha P and Gopalakrishnan K S 2001 J. Appl. Polym. Sci. 81(13) 3141–3148
[16] Gorton A D T 1967 Journal of the Rubber Research Institute of Malaya 20 1966.
[17] Quarteroni A 2014 Numerical Models for Differential Problems (Springer Publishing)
[18] Eymard R Normale E and De-Provence U 2000 Handb. Numer. Anal. 7(3) 2000
[19] Versteeg H K and Malalasekera W 2007 An Introduction to Computational Fluid Dynamics (Pearson Education Limited)
[20] Nichols C W and Hirt B D 1979 J. Comput. Phys. 42(3) 201–225
[21] Singha S and Sinhamahapatra K P 2010 Ocean Eng. 37(8–9) 757–769