# CFD Simulations for Studying Flow Behaviors in Dipping Tank in Continuous Latex Gloves Production Lines

W. Koranuntachai, T. Chantrasmi, U. Nontakaew



***Abstract*—**Medical latex gloves are made from the latex compound in production lines. Latex dipping is considered one of the most important processes that directly affect the final product quality. In a continuous production line, a chain conveyor carries the formers through the process and partially submerges them into an open channel flow in a latex dipping tank. In general, the conveyor speed is determined by the desired production capacity, and the latex-dipping tank can then be designed accordingly. It is important to understand the flow behavior in the dipping tank in order to achieve high quality in the process. In this work, Computational Fluid Dynamics (CFD) was used to simulate the flow past an array of formers in a simplified latex dipping process. The computational results showed both the flow structure and the vortex generation between two formers. The maximum shear stress over the surface of the formers was used as the quality metric of the latex-dipping process when adjusting operation parameters.

***Keywords*—**Medical latex gloves, latex dipping, dipping tank, computational fluid dynamics.

## I. Introduction

MEDICAL latex gloves are the rubber product that made from liquid latex compound. An array of glove-shaped ceramic formers are brought into continuous production process by a long chain conveyor. The production process consists of various sub-processes such as former cleaning, former drying, coagulant dipping, latex dipping, gelling, vulcanizing, beading, and stripping [1]-[3]. One of the most critical sub-processes in these long production lines is latex dipping (see Fig. 1). Latex film formation is a chemical process in which the latex film is formed on the former surface while the formers are dipped into latex compound in a dipping tank [4]. The formers are later put through vulcanizing process in which this film turns into medical latex gloves.

Currently, one of the most typical designs of dipping tanks is called “the island design” [5]. In this design, the latex compound flow is divided into two sides. On each side, latex compound is circulated in a simple loop while driven by a slowly rotating propeller. The formers are lowered into the long straight section of this channel flow, while the latex compound is driven to flow generally in the same direction as the formers do to reduce the relative speed between the flow and the former surface, thus supposedly allowing a better formation of the latex film.

Fig. 1 Latex-dipping process in a production line

The final product quality can be influenced by several fluid flow phenomena that occur in the straight dipping section. These flow phenomena are results of a combination of various factors such as geometrical dimensions, latex compound properties, and the conveyor speed. Two flow phenomena should be avoided in the latex-dipping tank under consideration. They are turbulent open-channel flow [6]-[8] and (unsteady) vortex shedding of flow past an array of formers. As such, latex-dipping tank design parameters must be chosen appropriately to avoid these unwanted flow phenomena.

This paper presents a series of Computational Fluid Dynamics (CFD) simulations [9], [10] to find an appropriate design within the safe parameter ranges (in which the unwanted phenomena would not happen). Both the flow structure and the vortex generation between two adjacent formers are shown after the computational calculation process is completed. the quality metric of the latex dipping process was the maximum shear stress over the surface of the formers at various operation parameters

## II. Model Problem

In this work, the model problem is defined as follows. A simplified drawing of a latex dipping tank is shown in Fig. 2 (a) The tank is designed to support both sides of the conveyor chain. On each side, a conveyor chain is attached to an array of formers, moving streamwise in a single line. This chain conveyer system is generally called “single-former”.

Fig. 2 (b) shows a realistic example of a latex-gloves former. For this work, the geometry is approximated to a cylinder with

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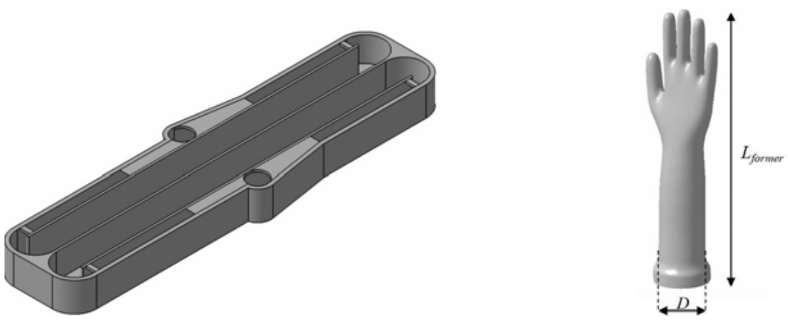
diameter $D$ and length $L_{former}$. Average values of $D$ and $L_{former}$ are 7 cm and 40 cm, respectively, and these values are used here. In practice, these values can vary based on the gloves size being produced.




(a) (b)

Fig. 2 (a) A simple latex dipping tank design; (b) An example of a latex-gloves former

The tank design parameters are the geometrical dimensions of the straight section of the dipping tank, the conveyor speed ($U_{conveyer}$), the dwell time, and the pressure gradient ($\partial P/\partial x$) provided by the driving propeller. The straight section can be simplified to an open channel flow with a rectangular cross section. Thus, the main geometrical dimensions are the length of the latex dipping channel ($L_x$), the width of latex-dipping channel ($L_y$), and the latex height from the bottom of the channel ($L_z$).

In general, the conveyor speed is designed in relation to the desired production capacity and the dwell time is directly related to the thickness of the rubber gloves. The dwell time is determined experimentally and is usually around 8-12 seconds. Given the dwell time and the conveyor speed, the tank length is thus fixed. The latex height from the channel bottom is typically set to 50 cm by production conditions.

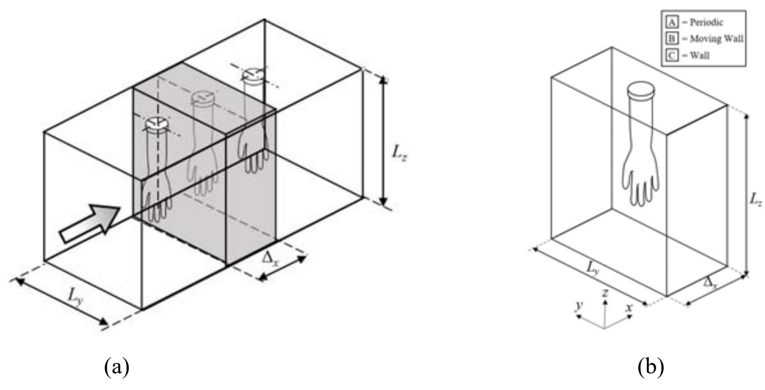
The remaining parameters – i.e., $L_y$, $U_{conveyer}$ and $\partial P/\partial x$ – cannot be determined in a trivial way. In this work, different combinations of these three parameters are analyzed. The tank width is allowed to change within 30-60 cm range, and the conveyor speed 0.2-0.6 m/s range. As for the pressure gradient, its limits are calculated based on enforcing absence of unsteady vortex shedding in the flow. Thus, Reynolds number of the flow based on the diameter of the former should be no more than 40 [11], [12].

The material properties of the latex compound depend on the chemical formula, which may vary from one factory to 0another. Here, a standard formula is considered. Nominal values of density ($\rho$) and viscosity ($\mu$) are 1,000 kg/m$^3$ and 200 cP, respectively. Note that the fluid is assumed to be Newtonian to simplify this analysis. In addition, former landing and departing regions are not considered and the flow is approximated as fully developed away from these regions.

## III. Numerical Setup

This section describes the simulation setup. The key idea is to assume that the flow is already in the appropriate regimes – laminar open-channel flow with no vortex shedding (or turbulent wake). A series of Computational Fluid Dynamics (CFD) simulations can then be quickly and efficiently performed under these assumptions (i.e., 3D, steady-state, and laminar). In this work, the commercial software ANSYS Fluent were used.

Fig. 3 (a) shows a schematic diagram of the simplified model problem and the flow direction. The driving pressure difference can be simplified to pressure gradient, $\partial P/\partial x = -\Delta P/L_x$ since it is assumed that the flow in this section is fully-developed. When defined as a flow through an array of formers, the flow behavior is similar for every former, so periodic boundary conditions are used in the streamwise direction.




(a) (b)

Fig. 3 (a) A schematic diagram of the simplified model problem; (b) The computational domain in the differential analysis simulations

Fig. 3 (b) shows a computational domain used in the simulation. Latex flows from front to back. Only one former is included in the domain. The width of the domain is thus the center-to-center distance between two consecutive formers ($\Delta x$). The top boundary condition is free shear wall and the other sides are moving walls with the given conveyor speed (in the opposite direction).

Consider the flow regime to determine the range of the pressure gradient to avoid the unwanted flow phenomenon. Since it is assumed that the flow in this dipping section is the fully developed, the velocity profile $u(y,z)$ of an open channel flow can be obtained by solving the Poisson's equation [6], [7]:

$$-\frac{\partial P}{\partial x} + \mu \nabla^2 u = 0 \tag{1}$$

In the moving reference frame (of fixed formers), the velocity profile past the former is then:

$$u_{rel}(y,z) = U_{conveyor} - u(y,z) \tag{2}$$

The relative velocity is different at each height level on the two formers. Conservatively, one can use the highest relative velocity, $u_{rel,max}$, in the topmost section, for calculating the Reynolds number to determine if unsteady vortex shedding will occur. The highest relative velocity will occur at the top surface and farthest way from the tank centerline (but still hitting a former). The Reynolds number of the flow past a former can then be obtained as:

$$\mathrm{Re} = \frac{\rho U_{rel} D}{\mu} \tag{3}$$

The flow regime here should be either creeping flow or laminar flow with only small recirculation bubble downstream from the cylinder. The Reynolds number for this should be no more than 40 [6]. This imposes a certain range of the design parameters, which will be called the "safe operating range" below.

Fig. 4 shows the standard structured mesh used in the simulation. The grid independence test and the grid convergence study are used to find the optimal grid condition. The total number of cells turned out to be around 880,000.

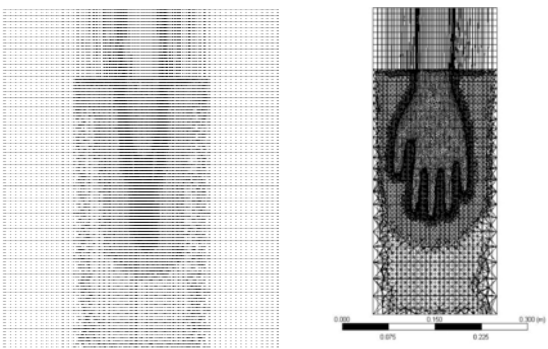


Fig. 4 The computational mesh

## IV. Simulation Results

The former flow pattern is as expected. It has a flow characteristic that is similar to a flow past a truncated cylinder. The relative velocity of the flow past the former, $u(x,y,z)$, varies with the height of the dipping tank. Separating layers of fluid creates a circulation behind the former. Laminar vortex separation (or vortex bubbles) spans the full gap between the former. The bubble varies in both size and shape at different horizontal cross sections along the length of the former. The left and right bubbles merge together behind the former behind the hand part to form an arch vortex. Finally, the fingertips of the former have a tip vortex (see Fig. 5).

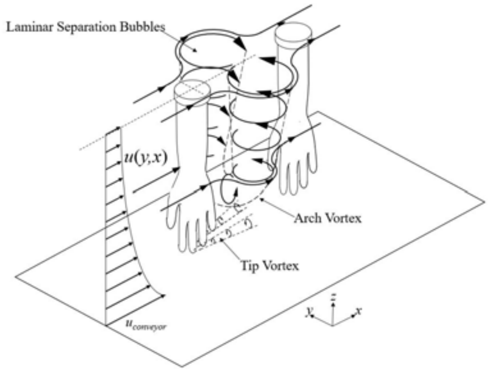



Fig. 5 The flow pattern between two adjacent formers

### A. Flow Structure

Consider a latex dipping at the conveyor speed of 0.35 m/s, the tank width of 40 cm, and the latex height of 50 cm. From the flow regime analysis not shown here, the safe operating range for the pressure gradient is approximately 2.6-5.0 Pa/m. Fig. 6 shows the streamline of fluid particles in the case of the lowest pressure gradient in the safe operating range of 2.6 Pa/m. The observed flow structure is similar to the expected one. The arch vortex can be clearly observed. Near the fingertips, the tip vortex is too weak to be seen.

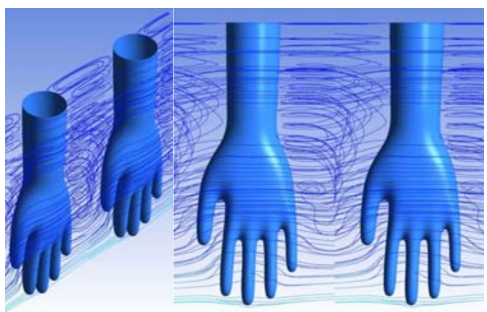


Fig. 6 The observed flow structure at pressure gradient of 2.6 Pa/m and conveyor speed of 0.35 m/s

Fig. 7 shows velocity field at four different depth levels: (a) the topmost level, (b) 100 mm deep, (c) 200 mm deep, and (d) 300 mm deep. In the topmost level, the laminar separation bubbles can be clearly observed. At the lower depth levels, it could still be seen but the bubbles dissipated much more quickly downstream. At every level, the laminar bubbles are asymmetry because of the shape of the former Dipping Quality and Shear Stress

*B. Dipping Quality and Shear Stress*

The quality of the latex dipping process depends on the completion of the latex film formation in the latex-dipping tank. As discussed above, the shear stress on surface of formers (from the simulation), can be used as a quality metric of the latex dipping process. More accurately, it is the *maximum* shear stress ($\tau_{max}$) over all locations on the surface of the formers, since a single-location defect can result in rejection of the final product.

The topmost cross section in the computational domain is used to consider $\tau_{max}$ since it is the position with the most reported defect problems. Again, consider the case with the conveyor speed of 0.35 m/s, the tank width of 40 cm, and the pressure gradient of 2.6 Pa/m. Fig. 8 (a) shows the shear stress vectors at different angular positions ($\theta$). The angle position is defined to be zero degree on the rightmost point and increase in the counter-clockwise direction. Fig. 8 (b) shows the shear stress ($\tau$) as a function of the angular position. It can be seen that the maximum shear stress of 0.499 Pa occurs at the angular position of 96.3°.

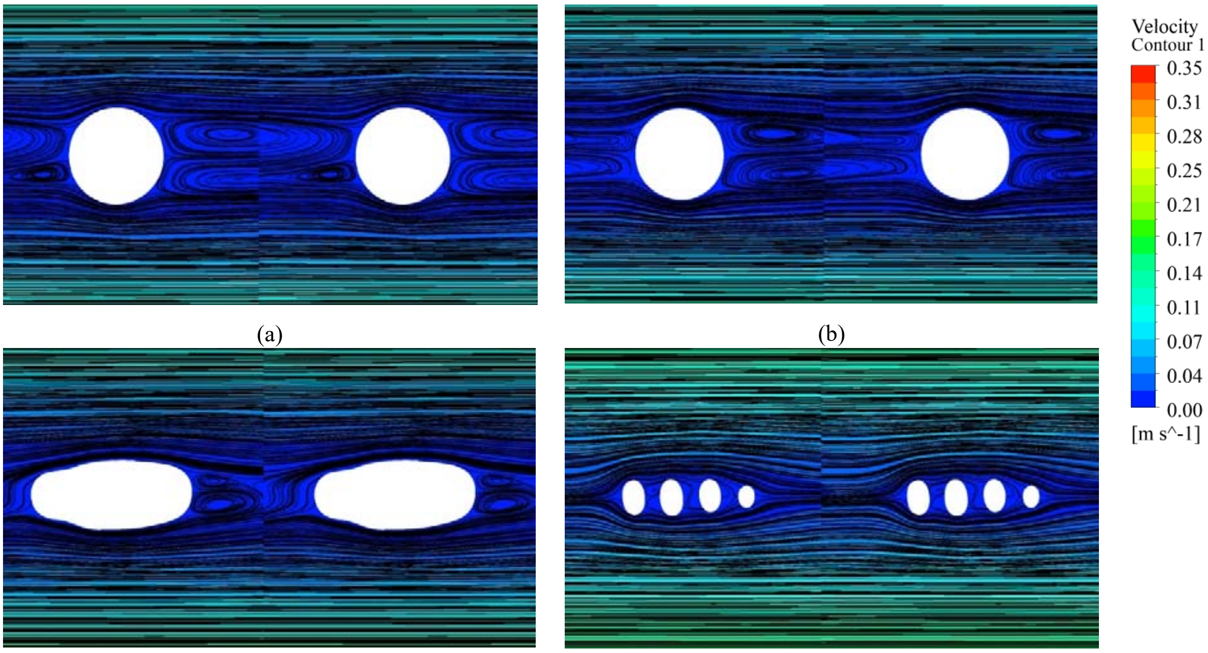
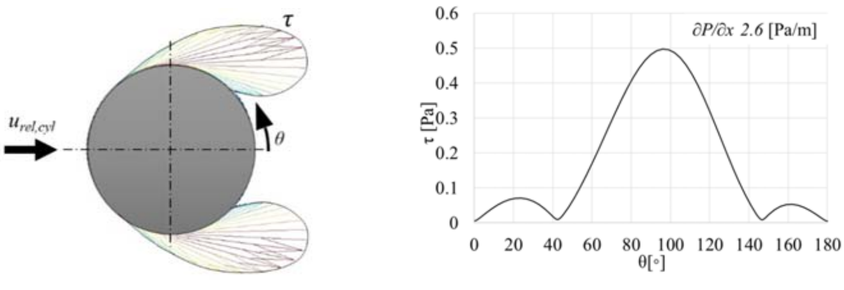



Fig. 7 Velocity field in horizontal planes at different depth: (a) the surface level, (b) 100 mm deep, (c) 200 mm deep, and (d) 300 mm deep




(a) (b)

Fig. 8 (a) Shear distribution on top section of former; (b) $\tau$ as a function of $\theta$ for conveyor speed of 0.35 m/s, tank width of 40 cm and $\partial P/\partial x$ of 2.6 Pa/m

Next, consider fixing the tank width at 40 cm as before and varying the pressure gradient in the safe operating range of 2.6-5 Pa/m. For each value of the pressure gradient, obtain the maximum shear stress and plot the latter as a function of the former. Fig. 9 shows such a plot, and it can be seen that there is a local minimum around 4.2 Pa/m. This point is named the "Critical Pressure Gradient" or CPG point in this work. Recall that the main objective here is to minimize $\tau_{max}$, hence the CPG is the optimal pressure gradient for a given tank width and a given conveyor speed.

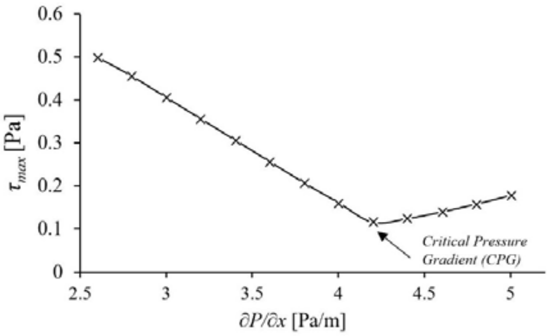



Fig. 9 The $\tau_{max}$ as a function of $\partial P/\partial x$ for conveyor speed of 0.35 m/s and tank width of 60 cm

As the last step, consider varying the conveyor speed and the tank width. For each pair, an optimal pressure gradient (which is the CPG) can be found. Fig. 10 shows the CPG as a function of both conveyor speed and the tank width. It can be seen that the CPG increases (that is, the flow needs a higher driving pressure gradient to be optimal in dipping quality) when the tank is narrower or when the conveyor speed is faster.

## V. Conclusions

This paper shows a systematic procedure to choose the design parameters for a latex-dipping tank by combining analysis and CFD simulations. The main parameters to optimize are the driving pressure gradient and the tank width, as the conveyor speed is typically fixed by the design of the entire production line.

The first step of the analysis is to determine a set of all possible ($U_{conveyor}$, $L_y$, $\partial P/\partial x$) pairs that will not result in turbulent open-channel flow nor laminar vortex shedding, these are unwanted flow phenomena. This results in the so-called safe operating range of the design parameters. The next step involves a series of steady, laminar CFD simulations to determine the maximum shear stress on the former surface. For each simulation, $U_{conveyor}$, $L_y$ and $\partial P/\partial x$ are varied and $\tau_{max}$ is obtained. It turns out that at fixed values of $U_{conveyor}$ and $L_y$, there exists a critical $\partial P/\partial x$ that will yield the minimal $\tau_{max}$. The pressure gradient at this point is called the "Critical Pressure Gradient (CPG)." This pressure gradient should be used to operate the latex dipping tank for the optimal dipping quality.

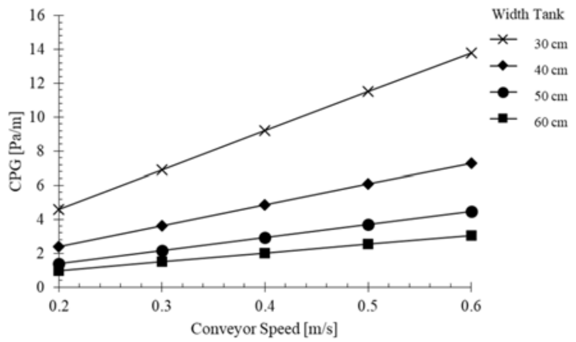



Fig. 10 The optimal operating pressure gradient (CPG) as a function of the conveyor speed and the tank width

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