CFD Modelling of a Highly Viscous Liquid Film on Rotating Vertically Disk

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Abstract. Hydrodynamic behaviour of the liquid film in rotating vertically disk reactor, that is partially immersed in a liquid bath, was investigated using computational fluid dynamics (CFD). A model for the fully free boundary problem of the rotating disk, that drags a thin film out of the bath is set up. The depth of the disc used 35% of the disk center to the liquid surface. Simulations were carried out using the volume of fluid method and compared with empirical correlations published in literature. The dominant factors that determine the film thickness are identified as a function of angular position, radius, rotating speed, viscosity and surface tension. The liquid film variation in the surface tension, and the liquid film dragged into the liquid are particularly investigated.

1. Introduction
The literature about liquid film flow on the horizontally rotating disc has already much discussed [12, 15], but for the vertically rotated, is still slightly discussed. Different with many horizontal flow cases, liquid film flow in vertically rotating disc, the thing that needs to be concerned is the liquid that is dragged out of tank because disk rotation. As the result, formed thin liquid flow that was patched to the disk surface, as large as the disk surface that was not dyed in the water. Liquid dynamic factor is still not completely investigated, although there were several general opinions and solutions about film thickness profile.

The aim of the study was visualizing the formation of liquid film that has the high vicious characteristic in the vertically rotating disc, with the position of the disk drown partially in the water in reactor tube. It is important to be known that the result of the film formation process said that the distribution of film thickness at different radial and angular position on the disk surface is not the same. The result showed that the flow which was flowing on the disk has the effect that cannot be ignored in the film formation process on the disk rotation. Computation model from thin film liquid flow consists of liquid tank, which is limited by reactor tube’s wall in each sides, with free surface and the liquid was exposed to other liquid, that was air in the application. [2, 3, 13].
In order to describe physical phenomena from liquid film flow, Navier-Stokes equation was used. This can be seen in the cylinder coordinate form [1, 4]. In this study, CFD code that used was ANSYS Fluent and Volume of Fluids method used to track and know free surface.

In the film formation modeling, it was important to calculate the force balance, as form and stability of the thin film was controlled by applied force: viscous, inertial, surface, tension, centrifugal, Coriolis, and gravitational force. For the disc that is vertically rotating, with low velocity scale at 1-6 rpm, Coriolis force can be ignored at the first scale, as the Coriolis was in the same scale with inertial scale, followed by lubrication theory [5, 8, 9].

2. Material and Methods

Numerical simulation was done using CFD Software in the purpose to get the detail from the flow that cannot be obtained from the experiment. The software used was ANSYS 16.2 Academic Package. To geometrical modelling used design Modeler with the determination of grid’s and node’s amount using meshing. The iteration calculation of CFD simulation using Volume of Fluids (VOF) method.

The system used in the vertically rotating disc’s study was semi-circle shaped tank, accompanied with rotating disk inside, the working fluids that were used were water and air.

2.1 Boundary Condition

Boundary condition model
1. Flow inlet and outlet boundaries :
   a. Free liquid surface.
   b. The limit of water surface on the disc, the flow velocity was set as $u = (\text{no-slip})$
2. Wall boundaries :
   a. Rotating disk wall as moving wall
   b. At the upper wall, lower wall and body as stationary

| Table 1. Solver Transient Computation Parameter Setting |
|--------------------------------------------------------|
| Computation Parameter                  | Computation Parameter Setting               |
| Tipe meshing                             | Hexahedral                                  |
| Discretization                          | Gradient (Least Square Cell Based),         |
|                                          | Momentum (Second Order Upwind),             |
|                                          | Volume Fraction (Geo-Reconstruct)           |
| Pressure-Velocity Coupling              | PISO                                        |
| Eulerian parameter                      | Multi-Fluid VOF Model                       |
| Contact angle (°)                       | 10                                          |

| Table 2. Operational Condition That Was Used |
|----------------------------------------------|
| Parameter               | Value                      |
| Rotational speed        | 10 rpm                     |
| Air                      | Properties of air :        |
| Liquid 1                | - Temperature (°C) : 27    |
|                         | - Density (kg/m$^3$) : 1.2 |
|                         | - Viscosity (kg/m.s) : 1.8x10$^{-5}$ |
| Liquid 2                | Water                      |
Properties of water:
- Temperature (°C): 26
- Density (kg/m³): 998.2
- Viscosity (kg/m.s): 0.001

Disc surface shape
Flat surface of disc

3. Result and Discussion
The gained data from this experiment was obtained through Computational Fluids Dynamics simulation method using software ANSYS 16.2 Academic Package. Used modelling in this simulation was laminar fluids flow modelling with unsteady-state method that was done at time step 0.0001s, number of time step 60,000 with maximal iteration per time step was 10. The fluid used was multiphase, which was liquid and gas phase. Where the liquid phase was liquid with high viscosity ($\mu = 10$ kg/m.s) and gas phase used was air. This simulation was using batch system. The tank used was horizontal cylinder shaped with the diameter was 27cm with disc that has 23cm diameter rotating inside the tank.

This simulation using water-air surface tension 0.0728N/m. Meanwhile contact angle that was used was $10^\circ$ so hydrophilic situation was formed between solid wall and fluid, so it was expected that the liquid can be dragged out and patched well to the disc surface. In the simulation of thin flow formation from the physical aspect that was free surface between different fluids, in this study was water and air; surface tension force that was exist on the free surface; and wall adhesion, with arranging contact angle between solid wall and water-air interface tangent on the wall that will be formed when liquid droplet made contact on the solid wall surface [7].

There were some things that need to be concerned in the simulation of thin layer formation from the physical aspect, they were the existence of free surface among the different fluids, the existence of surface tension force at the free surface, and the existence of adhesion force, with arranging the contact angle between solid wall and water-air interface tangent at the wall that will be formed when liquid droplet made contact at the free solid wall surface. In the previous study the thin film flow can be characterized using the non-dimensioned parameter like capillary number, Froude Number and Webber Number. [10]

![Figure 1](image.png)

**Figure 1.** Liquid distribution ($\mu=10$ kg/m.s), front Look, transient condition, In H=2.5 cm, $\omega=20$rpm, At t= (a) 0.1s;(b) 0.495 s;(c) 1.435 s;(d) 2.09 s;(e) 3.15 s;(f) 4.00 s;(g) 5.35 s;(h) 6.65 s;(i) 7.95 s.

**Figure 1.** showed transient simulation result for the smooth disk that was rotated with 20 rpm velocity with liquid viscosity 10 kg/m.s. Simulation showed that in 7.95 seconds it was exceeding 1 rotation Can be seen Front look visualization, liquid film can be formed in different thickness at angular position.
This liquid film thickness, if referred to the liquid film thickness equation by Miah [11], explained in formula below.

$$h' = 2.61 \text{Re}^{0.2} \text{Ca}^{0.1} \text{Fr}^{0.32} (r/R)^{0.36} \theta^{-0.16}$$  \hspace{1cm} (1)

The change from film thickness and the form/shape of thin film can be characterized with Froude Number (Fr). The simulation was also indicating Capillary Number (Ca) and Reynolds (Re) become the important parameter, the comparison of the true disk radius with simulation (r/R) and contact angle (θ). As the addition, the effect of surface tension in liquid thickness profile can be indicated from Webber, where \( \text{We} = \text{Re} \times \text{Ca} \). Liquid film thickness result using Miah [11] equation was explained through Figure 2.

![Figure 2. Liquid film thickness in different viscosity, at w=3rpm, referred to Miah et al., 2016](image)

It can be seen that higher the liquid’s viscosity, thicker the value of “h” (the liquid film thickness). In Figure 2, there was different liquid film thickness with different viscosity. In this study, with using high viscous liquid (\( \mu = 10 \text{ kg/m.s} \)), was clearly different with low viscous liquid [6, 7] at temperature of water 26°C, \( \rho = 0.99681 \text{ gr/cm}^3 \); \( \nu = 0.8774 \times 10^{-6} \text{ m}^2\text{s}^{-1} \). Can be clearly seen the viscosity factor was really influencing in the formation of liquid film besides rotational velocity factor.

4. Conclusion
The visualization of high viscous liquid film formation on the vertically rotating disk, with the position of the disk partially immersed was simulated well. In this study, influenced factor toward liquid film formation was identified, that was viscosity. With the Influenced forces, showed in Reynolds number, Froude number, and Capillary number.

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