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Computational Fluid Dynamics Assessment of Flow Characteristic of Thin Liquid Film over Smooth and Corrugated Rotating Disk Surface

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Process Intensification (PI) is used for analysis and design of innovative equipment and processing methods with substantially improved sustainability, efficiency and environmental performance. PI can be categorised into two, which are process-intensifying equipment and process-intensifying method. Rotating disk reactor is one of the equipment that involves PI that leads to rapid mixing and short residence time. To have a better understanding of the hydrodynamics behaviour of the thin film formed over the rotating disk surface; in this paper, thin liquid film flow over the smooth and corrugated rotating disk surface has been performed using 2-dimensional Computational Fluid Dynamics (CFD) simulation. Grid independence analysis of computational domain has been performed. The volume of fluid (VOF) model is used to simulate the flow characteristic of the thin liquid film. The comparison of thin liquid film flow over smooth and corrugated rotating disk surface has been carried out for liquid inlet velocity, rotational speed and liquid inlet location towards the thin liquid film thickness. The increment of disk rotational speed and liquid inlet velocity results in higher thinning effect of film thickness over the rotating disk surface. The simulation result showed that the flow of thin liquid film over the smooth rotating surface exhibits more consistent thickness and settle down earlier compared to the flow over the corrugated surface. The right and left liquid inlet locations have similar convergence at the same velocities. It can be concluded that the liquid inlet locations do not have a significant role in the formation of the thin film flow, although it is hypothesised that the liquid inlet located in the middle would be an optimum configuration as designed in the previous experimental and numerical studies.

1. Introduction

The research on process intensification (PI) technique has been becoming broader in the process industries. Improvised steps that are used in the name of PI are based on developments that go further than any traditional process engineering applications. More novel equipment and techniques have been implemented to transform chemical plants into compact, safe, energy-efficient and environment-friendly sustainable processes (Stankiewicz and Moulijn, 2000). PI was then classified into two, which is equipment and methods. The concept of PI in the early 1990’s was attentive on the application of centrifugal force, compact heat transfer, intensive mixing and combined technology that simplified the overall process, according to a study by Ponce-Ortega et al. (2011).

In the context of PI for reactors, the rotating disk reactor (RDR) is one of them. RDR is gaining popularity in carrying out rapid mass and heat transfer processes (Aoune and Ramshaw, 1999) and continuous multiphase reactions of nanoparticles (Parisi et al., 2011) since they offer large interfacial area and short residence times. RDR, when compared to the traditional batch reactors, is able to promote an ideal hydrodynamics environment for the enhancement of product quality, reduction of reaction times and the selectivity enhancement. In RDR, the liquid is fed into the center of a rotating disk that is usually rotating at up to 3,000 rpm, which generates thin, unstable and wavy liquid film over the disk surface. The aim of this research is to simulate the multiphase flow of thin liquid film flow over the smooth and corrugated rotating disk surface and describe the flow characteristics

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using the Euler-Euler approach. With the help of the information generated from the CFD simulation, the effects of various velocity inlets, disk rotational speeds, and liquid inlet positions on the thin liquid film flow thickness over the rotating disk were investigated.

2. Methodology

The multiphase flow of thin liquid film over rotating disk surface in this study consists of two phases with air as dispersed phase and liquid water as continuous phase over the rotating disk. The Euler-Euler approach is preferred for a majority of multiphase flow CFD simulation. The volume of fluid (VOF) model is one of the most widely used and important multiphase models for the immiscible fluids, where the position of the interface between the fluids is of interest. The VOF model mainly focuses on tracking the multiphase liquid flow interface. The rotating disk in RDR generates the thin liquid film flow under the effects of centrifugal forces.

2.1 VOF Model

The Euler-Euler approach of the multiphase modelling treats each phase individually as one volume of a phase cannot be occupied by another phase. Phases are seen as physical volume fraction, where the fractions are assumed to be a continuous function of space and time, whereby their total sum will equate to one as per Eq(1) (Fluent Inc, 2003).

$$\sum_{q=1}^{n} \alpha_q = 1 \qquad (1)$$

Since there are two phases involved, the gas phase (air) and the liquid phase (water), the following volume fraction equation (Fluent Inc, 2003) can be deduced.

$$\alpha_g + \alpha_l = 1 \qquad (2)$$

The volume fraction of each phase is deduced from the individual continuity equation (Fluent Inc, 2003):

$$\frac{\partial}{\partial t}(\alpha_g \rho_g) + \nabla.\left(\alpha_g \rho_g \underset{v_g}{\rightarrow}\right) = 0 \qquad (3)$$

$$\frac{\partial}{\partial t}(\alpha_l \rho_l) + \nabla.\left(\alpha_l \rho_l \underset{v_l}{\rightarrow}\right) = 0 \qquad (4)$$

2.2 Computational Domain

The rotating disk configuration in this study has a disk diameter of 13.2 x 10^{-3} m. The liquid was fed at an inlet positioned 1.5 x 10^{-3} m above the disk with an inlet diameter of 1.0 x 10^{-3} m. Figure 1 shows the computational domain of rotating disk with various liquid inlet locations and the domains were generated using the GAMBIT pre-processor software.

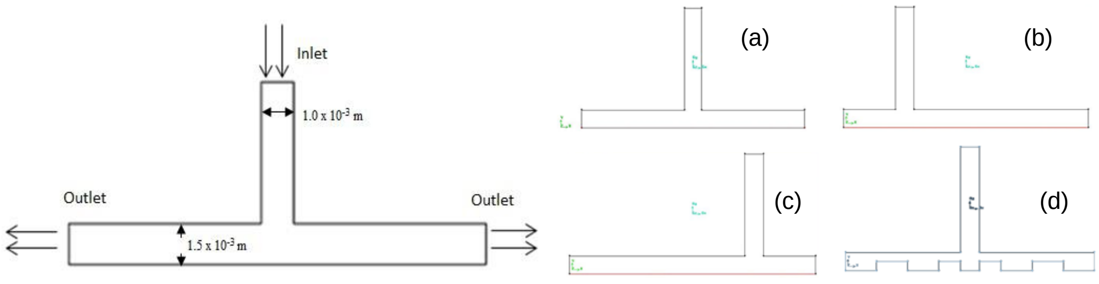

Figure 1: Computational domain of rotating disk configuration: smooth surface of rotating disk with a liquid inlet at (a) middle location (b) left side location (c) right side location and (d) corrugated rotating disk surface.

The boundary layer technique in specific regions of interest was used to observe the thin liquid film over the rotating disk. The uniform boundary layer algorithm was applied to the smooth rotating disk surface. For corrugated rotating disk surface, aspect ratio boundary layer algorithm was applied based on 50 % of the first percentage by 4 per rows. Quad element and sub-map type mesh faces was done on the smooth and corrugated surface of the rotating disk with a spacing of 0.0001 m. In grid independence analysis, four different grid sizes was used such as 0.00005 m, 0.0001 m, 0.0003 m and 0.0005 m, with a number of cells 10,656, 3,189, 302 and 375. The velocity magnitude convergence for all different mesh interval sizes shows that the flow velocity becomes stabilised and converged with the same trend line. Although the convergence plots of the velocity of the smallest mesh interval size seem to be more stable, it requires more computation time, which makes it less economic. Thus, the 0.0001 m mesh size was taken at the appropriate mesh size for the simulation model in this study. To measure the thin liquid film thickness formed over the rotating disk's surface, iso-line was created at four to five different locations in the post-processing step. The locations and their corresponding x-coordinates are as shown in Figure 2.

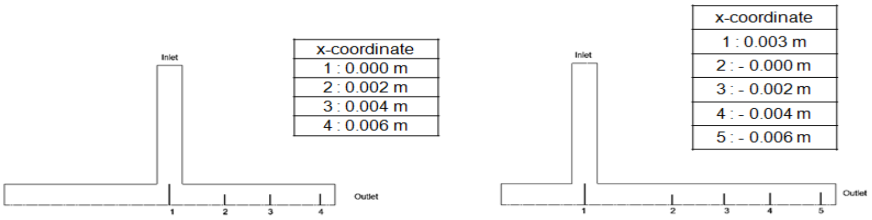

Figure 2: The locations of created iso-line in computational domain and their corresponding x-coordinate.

2.3 Simulation Model Parameters

Boundary conditions are specifications on how the flow in the domain enters and exits. The inlet is designated as velocity inlet to define the flow velocity and scalar properties of the flow. This is also only suitable for incompressible flows such as the ones in this research. The outlet is specified as pressure outlet with no backflow. Wall boundary conditions are used to bound fluids and solid regions. To specify the rotating disk's surface, the base wall is specified as moving rotational wall with a predefined rotational speed about the rotation axis.

Region adaption functions to mark cells inside or outside a defined hexahedron, sphere or cylinder to refine the particular region with a better resolution. In this simulation, the quadrilateral area above the surface of the disk and below the velocity inlet was adapted. The flow field of the entire domain has to be initialised first before proceeding with any calculations. The domain's calculation is computed from the velocity inlet. After initialising the entire flow field, patching is done for the area adapted earlier. The volume fraction variable for liquid (water) was selected with a value of zero to patch the hexahedron register. This will ensure that the area above the disk and below the inlet will have no liquid in it.

The formation of the thin film flow on the surface of the disk is highly dependent on the fluid velocity inlet to avoid divergence in the solver. As the simulation model has a turbulent viscosity ratio of 1 : 0, if the parameters exceed the ratio, the solver will not be able to complete the calculation. The simulation parameters used in this study was limited to the ones as shown in Table 1.

Table 1: Simulation model parameters and material properties

Description	Value	Comment
Model	-	Volume of fluid (VOF)
Solver	-	2D double precision solver (2ddp)
Liquid density	998.2 kg/m^3	water
Gas density	1.225 kg/m^3	air
Fluids velocity inlet	5.0, 10.0,15.0 m/s	specified
Disk rotational speed	100, 200, 300, 800 rpm	specified
Horizontal disk diameter	13.2 x 10^{-3} m	fixed value
Inlet boundary condition	velocity inlet	incompressible flow
Outlet boundary condition	pressure outlet	-
Wall boundary condition	rotational moving wall	100, 200, 300, 800 rpm
Time-steps	0.001 s	specified
Maximum iteration	30	specified

3. Results and Discussion

The hydrodynamics models were developed in FLUENT as shown in Figure 3. The thin liquid film flow can be observed with several parameters, namely rotational speed, fluid velocity and viscosity, residential time distribution and the mass flow rate. It can be seen that all three configurations, with varying inlet positions has obtained the same contours of volume fraction once they reached a steady flow state, which resulted in the formation of a stable thin film flow over the surface of the disk. From this observation, it can also be deduced that when the inlet is positioned either on the right or left, both the configurations acts as mirror images of each other, as for how the contour plots may suggest.

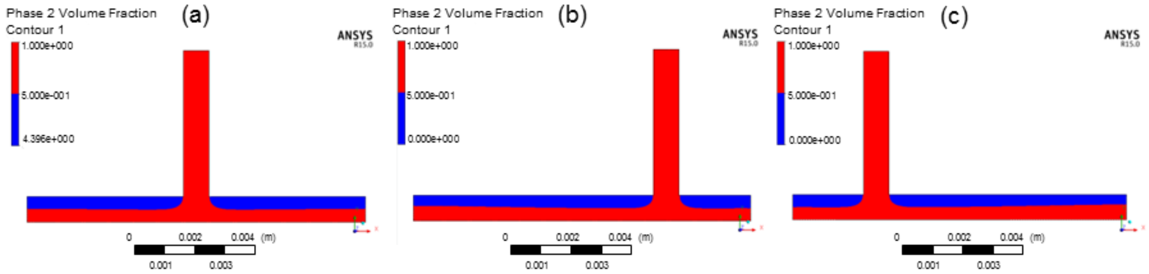

Figure 3: Contour plots of the volume fraction when the thin liquid flow achieves a steady state: liquid inlet at (a) middle location, (b) left side location and (c) right side location.

However, it was observed that the time for each configuration to reach the steady flow varies, as shown in Figure 4 (a). It can be said that when the inlet is positioned right or left, the results obtained are similar. The middle inlet achieved a steady flow earlier in comparison with the right and left inlets. The configuration of the spinning disk inlet position in previous studies that related to liquid film thickness formation was positioned in the middle; film thickness measurement (Burns et al., 2003), coating flows of viscous liquids (Parmar, 2003), thermographic analysis (Ghiasy et al., 2011), online measurement of residence time distribution (Mohammadi and Boodhoo, 2012), liquid film characterization (Bhatelia et al., 2009) and thin liquid film CFD modeling (Azudin et al., 2014). In order to further observe the time taken to reach steady flow over the spinning disk surface, the inlet velocity was varied as shown in Figure 4 (a), (b) and (c). Similarly, the time taken for the thin film flow to settle down when the inlet was positioned in the middle was the fastest. This is the first factor why the configuration with the inlet positioned in the middle is the optimum one.

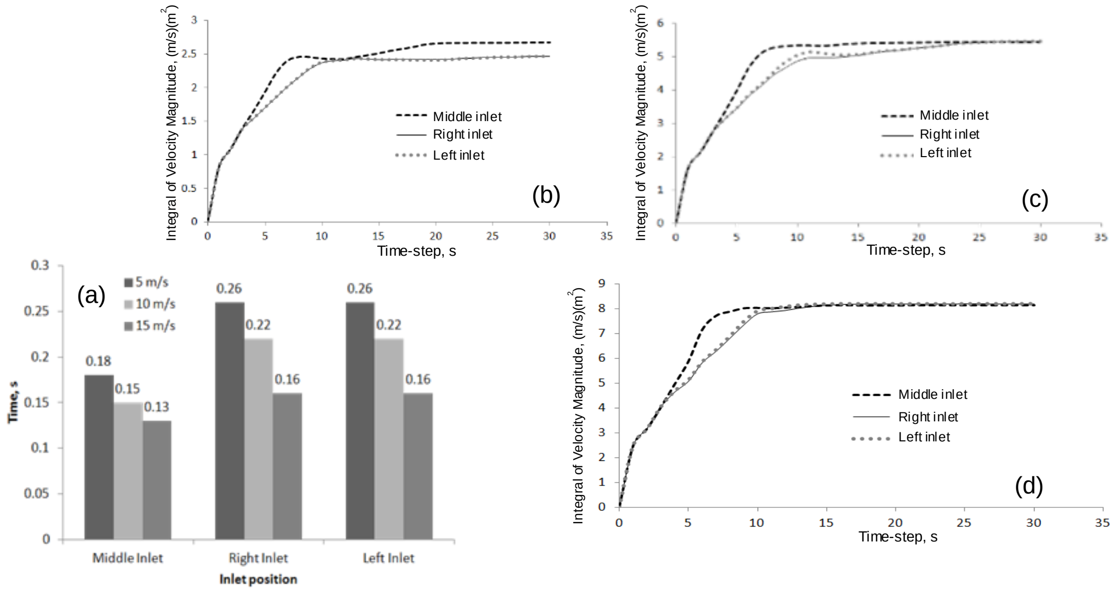

Figure 4: (a) Time taken for each configuration to reach steady state thin liquid flow with different inlet positions and inlet velocity. Comparison plot of the integral velocity magnitude convergence of all three different inlet positions for inlet velocity (b) 5 m/s, (c) 10 m/s and (d) 15 m/s.

Figure 5 (a) shows the comparison plot of integral velocity magnitude convergence of all three inlet locations at various inlet velocities. It can be seen all three velocities for all three inlet locations show the same trend with different values. The higher the velocity, the slower it reaches convergence. The effect of inlet location on the thin liquid film thickness at various inlet velocities was shown in Figure 5 (b), (c) and (d). The negative value of the location of the x-axis is just to show the magnitude of the flow in the domain configuration. The measurement was taken starting from the inlet until the outlet. All the three graphs show the same trend, with the thin film thickness on the spinning disk surface gradually decreasing from the end of the velocity inlet towards the outlet. For all the three different inlet locations, the thickness of the thin film formed decreases lightly when the inlet velocity of the configuration increases. However, as observed for the right and left inlet locations, there are little fluctuations as the thin film approaches the end of the outlet. This is probably due to the hydraulic jump phenomena.

The hydraulic jump phenomenon occurs when there is "sudden transition from supercritical to subcritical flow" (Schulz et al., 2015). When the flow travels from a high-velocity region to of a region of low velocity, the sudden change brings about a miniscule level change in the continuous flow of a liquid or fluid. This may be due to two criteria, which are the depth deficit and the air inflow conditions. In applying this phenomenon to the thin film flow formation on the spinning disk reactor's surface, the first criterion is only possible when there is a difference in the surface of the disk, where the design of the disk might be corrugated as in Figure 6 (b). The hydraulic jump observed in this research is more fitting to the second criterion. This is because there is air present in the gap between the spinning disk surface and the housing of the reactor. As the water travels from the inlet towards the disk surface, rotational force tends to entrap the air as the water flows towards the outlet, causing the "jump" at some points.

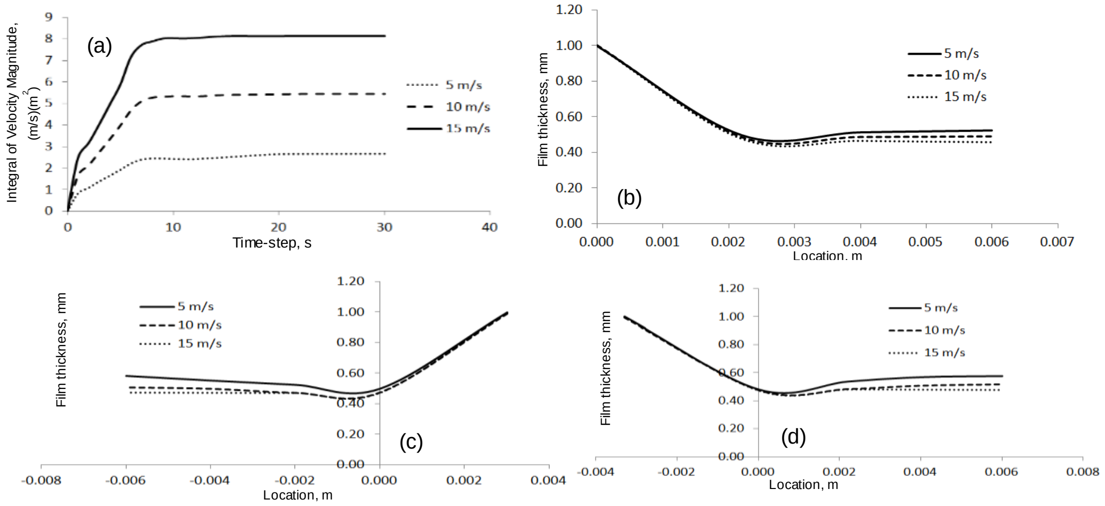

Figure 5: (a) Comparison plot of the integral velocity magnitude convergence of all three different inlet velocities. Comparison plot of the thin liquid film thickness for different inlet velocities (b) middle, (c) right and (d) left at 800 rpm of rotational speed.

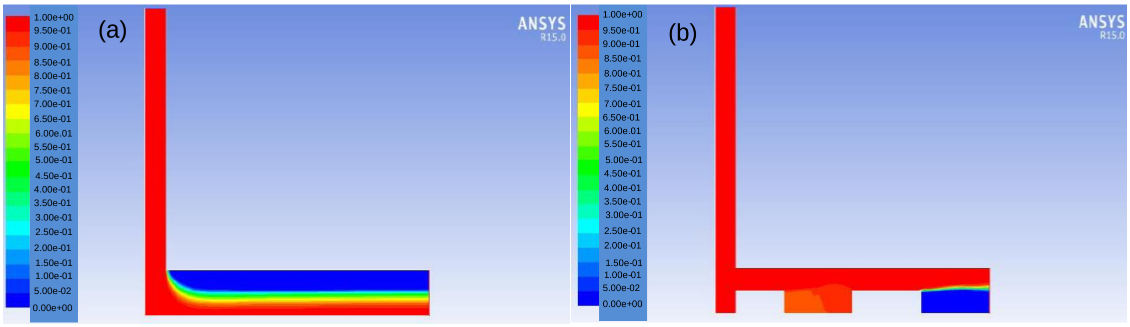

Figure 6: Contour plot of volume fraction of thin liquid film over (a) smooth rotating disk surface and (b) corrugated rotating disk surface.

The simulation results also show that the thin liquid film thickness behaved differently at various rotational speed in Figure 7. The disk rotational speed is one of the effective intensifying factors for thin liquid film flow over the rotating disk to achieve the higher thinning effect. The formation of a thin liquid film over smooth surfaces is more uniform in terms of liquid thickness as compared to the corrugated surface. This is because of the high interference caused due to the uneven structure on the corrugated rotating disk surface.

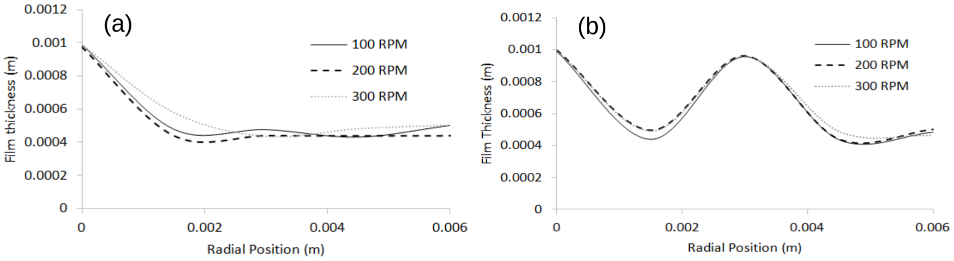

Figure 7: Thickness of thin liquid film flow over (a) smooth and (b) corrugated rotating disk surface at various disk rotational speeds.

4. Conclusions

The CFD assessment of VOF model the thin liquid film flow over the smooth and corrugated rotating disk surface with respect to different parameters has been investigated in this study using FLUENT software. It is observed that the thin liquid film flow exhibit difference values in the thickness when the inlet location, inlet velocity and disk rotational speed were varied. The thin liquid film thickness formed over the rotating disk surface have the same trend when the inlet location was changed. The most significant difference observed was the presence of the hydraulic jump when the inlet was positioned on the right or left side. The best configuration of the liquid inlet that can be concluded is in the middle of the RDR. The increment of disk rotational speed and liquid inlet velocity result in higher thinning effect of film thickness over the rotating disk surface. The results obtained proved that the liquid flow over the smooth surface settles down earlier than the corrugated surface. Smooth disk surface is basically suitable to be used in coating technology to get uniform film thickness over the disk. Corrugated disk surface may be suitable to be used in mass transfer application that needs rapid mixing of liquid or gas over the disk surface.

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