MODELING AND HYDRODYNAMICS STUDY OF A THIN LIQUID FILM FLOW OVER HORIZONTAL SPINNING DISK

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by

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MOHD FADHIL BIN MAJNIS
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LIST OF ABBREVIATIONS

3ddp	Three dimensional double precision solver
BC	Boundary condition
CCD	Charge coupled device
CFD	Computational Fluid Dynamics
FTIR	Fourier transform infrared
ODE	Ordinary differential equation
PA	Phthalic anhydride
PDE	Partial differential equation
PI	Process intensification
PTFE	Polytetrafluoroethylene
SDR	Spinning disk reactor
VOF	Volume of fraction

LIST OF SYMBOLS

		Unit
$a_{centrifugal}$	Centrifugal force	kgm/s^2
C	Concentration of diffusing substance	kg/m^3
C^*	Equilibrium concentration on the surface of liquid phase	kg/m^3
C_b	Bulk solute concentration	kg/m^3
C_{in}	Solute concentration in the liquid phase at the entrance	kg/m^3
D	Constant of diffusion coefficient	m^2/s
F	Body forces	kgm/s^2
f	Factor of instability	-
$F_{viscous}$	Viscosity force	kgm/s^2
h	Thin liquid film thickness	m
H_o	Initial thin liquid film thickness	m
h_R	Calculated thin liquid film thickness	m
K	Average coefficient of mass transfer	-
k	Liquid resistivity	Ωm
n	Number of data points	-
N_{cp}	Capacity factor	-
P	Pressure	kg/ms^2
Q	Volumetric flow rate	m^3/s
r	Radial coordinate in cylindrical system	-
R	Disk radius	m

$\bar{r}$	Normalized radial coordinate in cylindrical system	-
r_1	Radial coordinates of first electrode	m
r_2	Radial coordinates of second electrode	m
R^2	Correlation coefficient	-
R_{AB}	Electrical resistance	Ω
Re	Reynolds number	-
R_{in}	Radius of the disk at the entrance	-
R_o	Inlet radius of the disk	m
Ros	Rossby number	-
R_{out}	Radius of the disk at the edge	-
t	Time	s
$\bar{t}$	Normalized time	s
T	Stress tensor	-
$\bar{u}$	Flow velocity inlet	m/s
U_o	Inlet velocity of the liquid	m/s
u_r	Flow velocity at *r* axis in cylindrical coordinate	m/s
$\bar{u}_r$	Nondimensional flow velocity *r* axis in cylindrical coordinate	-
u_x	Flow velocity at *x* axis in Cartesian coordinate	-
u_y	Flow velocity at *y* axis in Cartesian coordinate	-
u_z	Flow velocity at *z* axis in Cartesian coordinate /z axis in cylindrical coordinate	-
$\bar{u}_z$	Nondimensional flow velocity *z* axis in cylindrical coordinate	-

u_θ	Flow velocity at θ axis in cylindrical coordinate	m/s
$\bar{u}_\theta$	Nondimensional flow velocity θ axis in cylindrical coordinate	-
V	Constant volume fixed in space with uniform density	m^3
V_A	Potential at electrode A	V
V_B	Potential at electrode B	V
V_D	Potential different between inner and outer electrodes on the disk surface	V
V_T	Potential across the whole circuit	V
x	x coordinate in Cartesian system	-
y	y coordinate in Cartesian system	-
z	z coordinate in Cartesian system/axial coordinate in cylindrical system	-
$\bar{z}$	Normalized axial coordinate in cylindrical system	-

Greek letters

δ	Hydrodynamics boundary layer	m
$\bar{\delta}$	Normalized film thickness	-
ε	Ratio of lubrication theory	-
η	Degree of desorption	-
θ	Tangential coordinate in cylindrical system	-
ρ	Fluid density	kg/m^3
υ	Kinematic viscosity	m^2/s
ω	Disk rotational speed	rpm

∂	Partial derivative symbol	-
μ	Viscosity of liquid	kg/ms
∇	Del operator	-
∇^2	Vector Laplacian	-

PEMODELAN DAN KAJIAN HIDRODINAMIK UNTUK ALIRAN SAPUT CECAIR NIPIS DI ATAS CAKERA BERPUTAR MENDATAR

ABSTRAK

Aliran saput cecair nipis di atas cakera berputar mendatar di bawah pengaruh medan emparan merupakan salah satu pelaksanaan dan kaedah dalam proses intensifikasi (pengamatan). Kajian hidrodinamik dan pembangunan model mekanistik amat perlu untuk menerangkan kelakuan aliran saput ini. Maka, persamaan Navier-Stokes dan persamaan resapan berolak digunakan untuk meramal tebal saput cecair nipis dan untuk menerangkan ciri percampuran di atas permukaan cakera berputar. Kesemua persamaan menakluk diselesaikan dengan kaedah perbezaan terhingga dalam dua dimensi berserta keadaan awal dan keadaan sempadan. Pakej perisian CFD, Fluent® 6.3 digunakan untuk penyelakuan model pecahan isipadu (VOF) yang berbilang fasa untuk aliran saput cecair nipis ini. Manakala, eksperimen dijalankan menggunakan rig ujian cakera berputar dengan cakera mendatar berkelajuan boleh ubah untuk mengesahkan model mekanistik yang telah dibangunkan seterusnya membuat perbandingan pemodelan hidrodinamik yang dibangunkan dalam perisian CFD. Keputusan yang diperolehi menunjukkan model mekanistik dan model CFD untuk ketebalan saput cecair nipis mencapai kesepakatan yang memuaskan dengan keputusan eksperimen dengan R^2 = 0.841 - 0.999. Sementara itu, pekali pemindahan jisim untuk kajian percampuran dibandingkan dengan hasil kerja oleh Tsibranska *et al*. (2009), dan keputusan menunjukkan kecenderungan yang sama di mana pekali pemindahan jisim meningkat dengan peningkatan kelajuan putaran cakera. Kajian percampuran yang melibatkan pengiraan pekali pemindahan jisim dan gambaran taburan zarah pencelup dapat

dirumuskan bahawa putaran cakera merupakan parameter penting untuk meningkatkan pemindahan jisim dalam saput cecair nipis di atas cakera berputar mendatar.

MODELING AND HYDRODYNAMICS STUDY OF A THIN LIQUID FILM FLOW OVER HORIZONTAL SPINNING DISK

ABSTRACT

A thin liquid film flow over horizontal spinning disk under influence of centrifugal field is one of the implementation and method in process intensification. Hydrodynamics study and development of mechanistic model is strongly desirable to describe this film flow behaviors. Thus, Navier-Stokes equations and convective diffusion equation were used for thin film thickness prediction and to represent mixing characteristic over the spinning disk respectively. All the governing equations are solved numerically by finite difference method in two dimension configuration, with initial condition and boundary condition. Moreover, CFD software package, Fluent 6.3® was used to simulate a multiphase of volume of fraction (VOF) model of this flow. Then, experiments were carried out in a spinning disk test rig with variable speed of spinning to validate the developed mechanistic model, and to compare with simulation in CFD. The result obtained have showed that the developed mechanistic model and CFD model for thin liquid film thickness were in satisfactory agreement with the experimental results with R^2 = 0.841 to 0.999. Meanwhile, the calculated mass transfer coefficients for mixing measures was compared with the work by Tsibranska *et al.* (2009). The results showed a similar trend in which the mass transfer coefficients increased as disk rotational speed increased. The calculated mass transfer coefficient and visualization of dye particles distribution in mixing characteristic in the present study showed that the speed of disk rotation was a significant parameter in enhancing the mass transfer in thin liquid film flow over a horizontal spinning disk.

CHAPTER 1

INTRODUCTION

Process intensification (PI) is presently one of the most noteworthy trends in chemical engineering and process technology. It is attracting extensive attention of the research world to work on novel equipment and techniques that potentially could transform our conventional concept of chemical plants. These developments were focused on PI, an approach that has been around for quite some time but has truly emerged only in past few years as a special and interesting discipline of chemical engineering. PI refers to complex technologies that replace large, expensive, energy-intensive equipment or processes with smaller, less costly, more efficient plants that combine multiple operations into a single apparatus or into fewer devices (Charpentier, 2005).

The philosophy of PI emerged during the late 1970s, initiating from the work by Prof. Colin Ramshaw and his co-workers at Imperial Chemical Industries (ICI) in the United Kingdom. The primary goal of their work initially was to reduce the capital cost of a production system. Then, PI has been on the upswing since a review written by Stankiewicz and Moulin was issued in 2000. PI is an engineering area where new methods and novel equipment, compared to those commonly used today, are developed using more compact design with the intention to reduce the capital cost of process systems, substantially decreasing equipment size, improve intrinsic safety and minimize their environmental impact. Meanwhile, companies and academia are addressing problems in process intensification, organizing workshops and even establishing departments on this subject. PI becomes a very broad discipline and includes expertise in many diverse fields. This intensified chemical system will take chemical engineering on a similar technological journey, as what electronics industries has transformed the way we live through miniaturization of electronics devices (Wegeng *et al.*,1999)

Wide range of application is offered by PI, applying the philosophy of PI to the construction and operation of the chemical process will result in many exciting developments. PI as an integrated multidisciplinary approach coupling chemical research and development, and chemical engineering has potential for breakthrough innovations that fundamentally and radically change chemical processes for selected applications (Becht *et al.*, 2008).

In Figure 1.1, an overview of equipment and methods employed in PI is presented. PI can be divided into two areas: there was process-intensifying equipment and process-intensifying methods (Stankiewicz and Moulijn, 2000). There can be some overlap, new methods may require novel types of equipment to be developed and vice versa, while novel apparatuses already developed sometimes make use of new and unconventional processing methods.

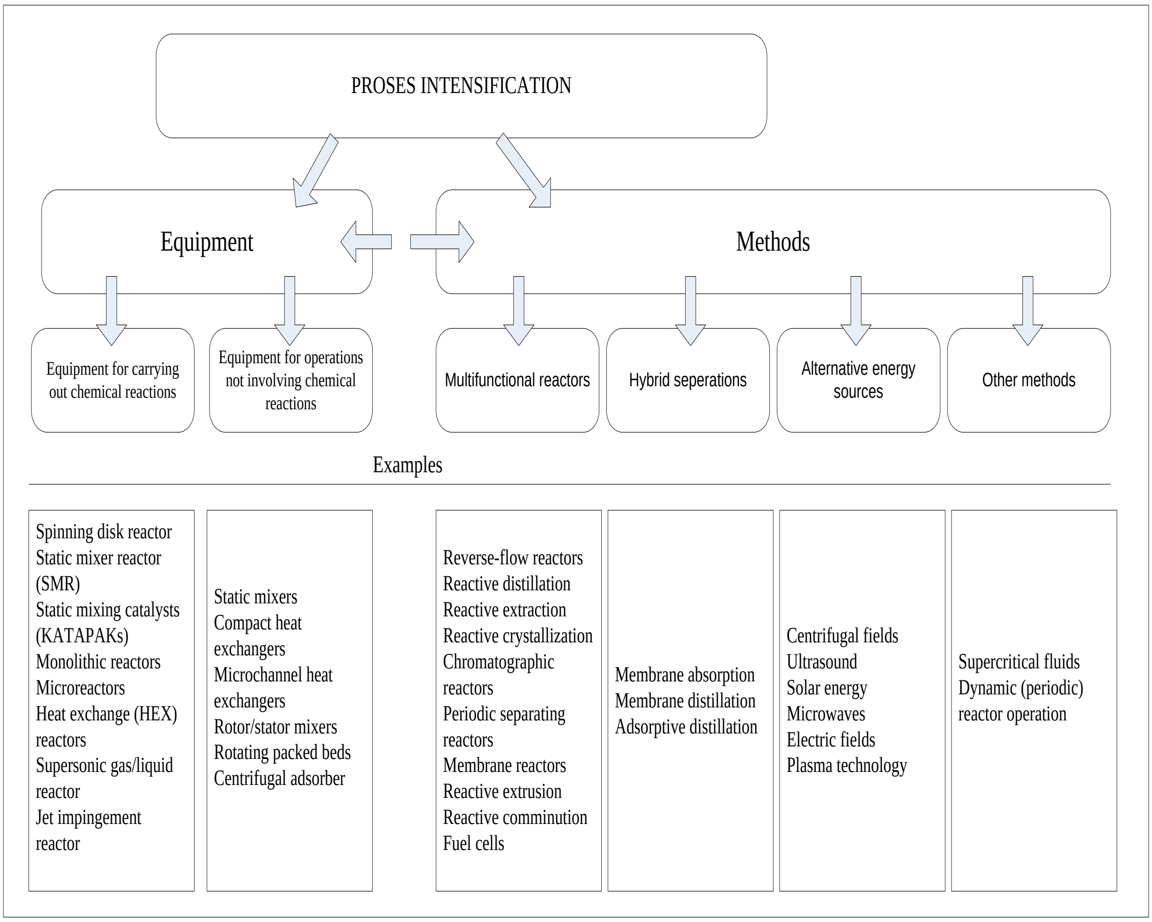

Figure 1.1: Process intensification and its component (Stankiewicz and Moulijn, 2000).

1.1 Research Background

1.1.1 Centrifugal Fields Exploitation in Process Intensification

The use of centrifugal fields as one of the process-intensifying methods in PI for chemical processing has generated much interest in recent years. For instances, it is used for coating disk, to disperse liquid in absorbers, humidifiers or dryers, to concentrate solution by evaporation, polymerization etc. The fluid acceleration creates an environment in which mass transfer rates are two or three orders of magnitude higher than rates achieved in conventional equipment.

Yarbro and Schreiber (2003) have presented annular centrifugal contactor in the actinide processing industry as an example of centrifugal field's exploitation in PI. In processing industry, all actinide elements which is lie between actinium and lawrencium with atomic numbers 89 - 103, are radioactive and potentially fissile which limits the amount of material that can be processed in a given unit operation to prevent a critically accident. Thus, glove boxes or remote-handling facilities are required for safety purpose, but they are expensive and have high maintenance and operational costs. Annular centrifugal contactors thus provides safer alternative which uses centrifugal force to mix and separate the liquids in a solvent extraction process. To compare the capacities and the degree of intensification for different types of contactors, a non-dimensional capacity factor, N_{cp} is defined as the ratio of total volumetric flow rate for both phase multiply by time basis per working volume of equipment. Figure 1.2 shows the comparison of size and capacity factor for several types of contactors for one hour operation. Moreover, the settling time for centrifugal contactors is significantly decreased from 240 s to 30 s for the extraction section.

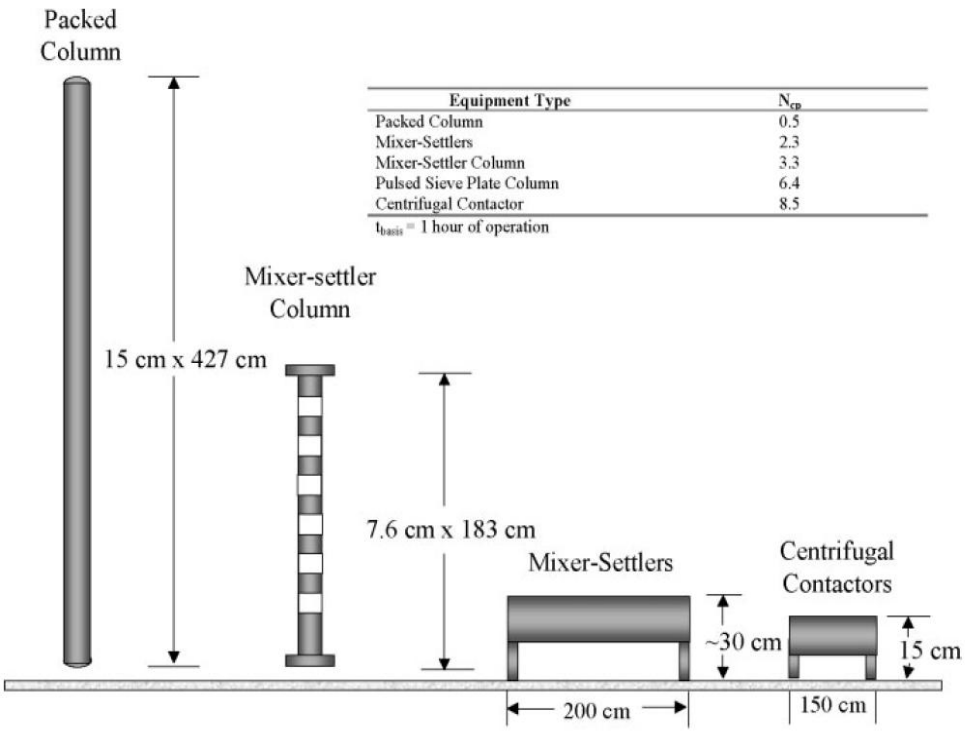

Figure 1.2: Comparison of size and capacity factor for several types of contactors (Yarbro and Schreiber, 2003).

In the rotating reference frame, the centrifugal force exists due to the spinning of the disk in certain rotation speed. Therefore, a spinning disk is capable of generating a very thin liquid film through high centrifugal acceleration over the spinning disk surface. This ability offers a wide range of opportunities for process conventionally limited by interfacial mass transfer such as crystallization of an active pharmaceutical (Brechtelsbauer *et al.*, 2001), polymerization of styrene (Boodhoo and Jachuck, 2000) and separation processes including absorption, extraction and distillation (Stankiewicz and Moulijn, 2000).

In spinning disk reactor (SDR), liquid is fed to the center of a rotating disk and as the liquid moves towards the edge then intense interfering waves are formed under the influence of the centrifugal force. The waves formed also produce intense local mixing. The liquid flow involves very little back mixing and is therefore almost pure plug flow (Protensive, 2000). Moreover, the residence time of the liquid film on the disk is short and typically in seconds. Figure 1.3 below showed the schematic diagram of SDR.

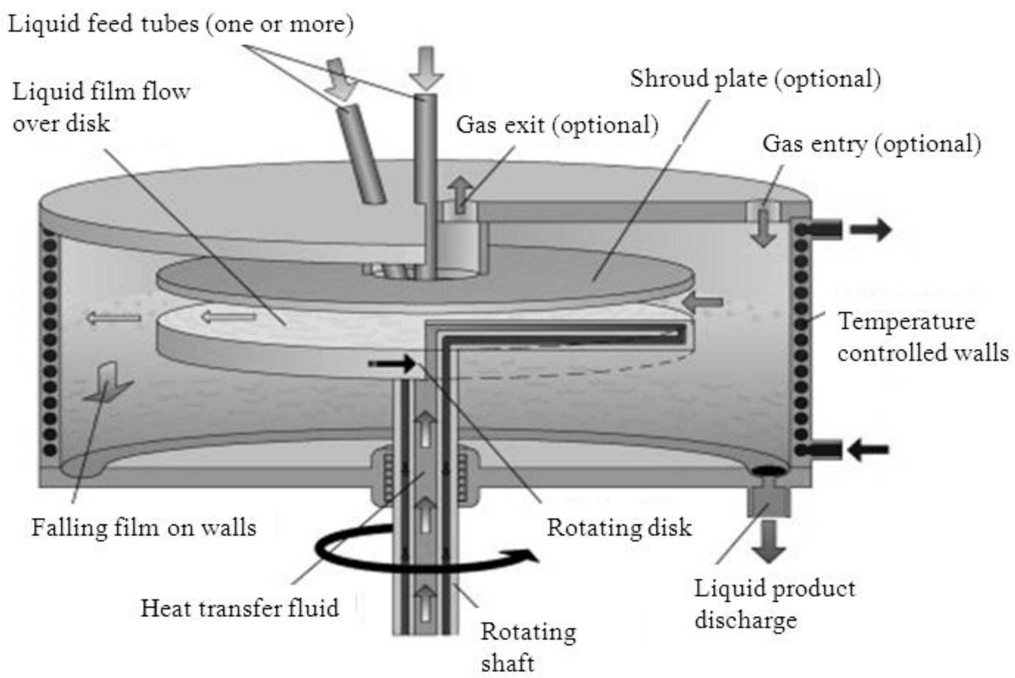

Figure 1.3: Schematic diagram of spinning disk reactor (Protensive, 2000).

1.1.2 Spinning Disk Technology

Many approaches have been made for intensifying processes, and one is continuous processing in spinning disk reactor (SDR). It is proposed as an alternative to traditional stirred tank processing technology whereby offering better control of product quality. The SDR relies on high centrifugal acceleration to generate a very thin film of liquid typically 100µm that moves on the surface of a disk spinning up to approximately 1000 rpm. Besides, it is also coupled with the film wave structure, results in high disk/liquid, liquid/liquid and gas/liquid heat and mass transfer coefficients. In addition, the liquid residence time on the disk surface only a few seconds. At very short residence times typically 0.1 seconds, heat is efficiently removed from the reacting liquid at heat transfer rates reaching 10000W/m^{2}K (Protensive, 2000).

1.1.3 Hydrodynamics of Thin Liquid Film over Horizontal Spinning Disk

The flow of liquids in thin films is frequently observed in everyday life as in flow of rain water on windows panes and roofs, flows in kitchen sink etc. Thin liquids films also find applications in industry as in during evaporation or condensation on a solid surface in a compact heat exchanger or cooling tower, spin coating in metal industries, and impingement cooling of solid wall with a liquid jet.

Figure 1.4 shows the operating principle of thin liquid film flow over a spinning disk. Radial thin film on the disk surface is formed when liquids are supplied over a horizontal spinning disk with various disk rotational speeds. The ideal configuration is when the liquid feed streams is supplied in the center of the disk; this will allows creating a maximum contact surface between the liquid and the disk as well as between the liquid and the gas phase above the film. Then, the liquids will be spread out into a thin film that flowing radially away from the stagnation point. The effects of inertia, viscosity, gravity and surface tension govern such flows.

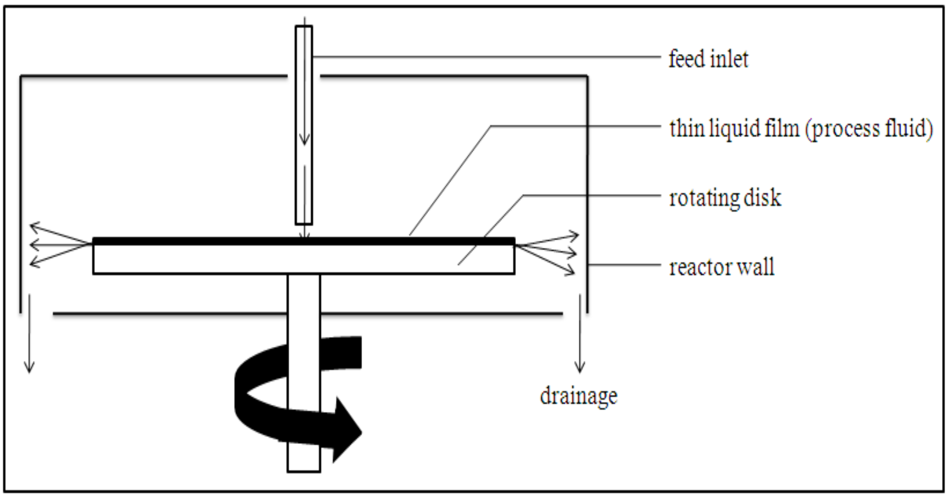

Figure 1.4: Thin liquid film over spinning disk operating principle.

In a stationary frame of reference, the liquid trajectory is a spiral with arms separated by a radial distance. However, the liquid trajectory is nearly radial in a rotating frame of reference. Thus, as the thin liquid film spreads out, the film thickness decreases under the action of an adverse hydrostatics pressure gradient and the effects of centrifugal force. The liquid leaves the disk as its edge after which it can be collected.

Collectively, the flow of the liquid film as it moves from the center of the disk to the edge is essentially unstable and extremely complex. Therefore, most of the hydrodynamics studies are considered simplified version of the film flow as the basis of the operating model, such as the film is assumed as laminar, incompressible, circumferentially uniform and stable flow (Emslie *et al.*, 1958; Matsumoto *et al.*, 1973; Naletova *et al.*, 1995; Lingwood, 1996; Auone and Ramshaw, 1999; and Peev *et al.*, 2006).

Works by Burns *et al.* (2003) have determined the different zones of behavior on the spinning disk when thin liquid film flows over it as shown in Figure 1.5. A natural division between the regions in two dimensional Pigford model by Wood and Watts (1973) and Nusselt model can be applied to provide a spin-up zone that surround the injection and acceleration zones. Beyond this zone the flow is synchronized with the disk rotation and the radial velocity profile is close to the Nusselt model, but inside this zone it may deviate considerably from the Nusselt model. To estimate the extent of the spin-up zone, the maximum turning point was used as a guide as shown in Figure 1.6. By calculating these zones, it allows us to know the significant of tangential motion (relative to the disk) extends and it also engineering tool to use in disk design.

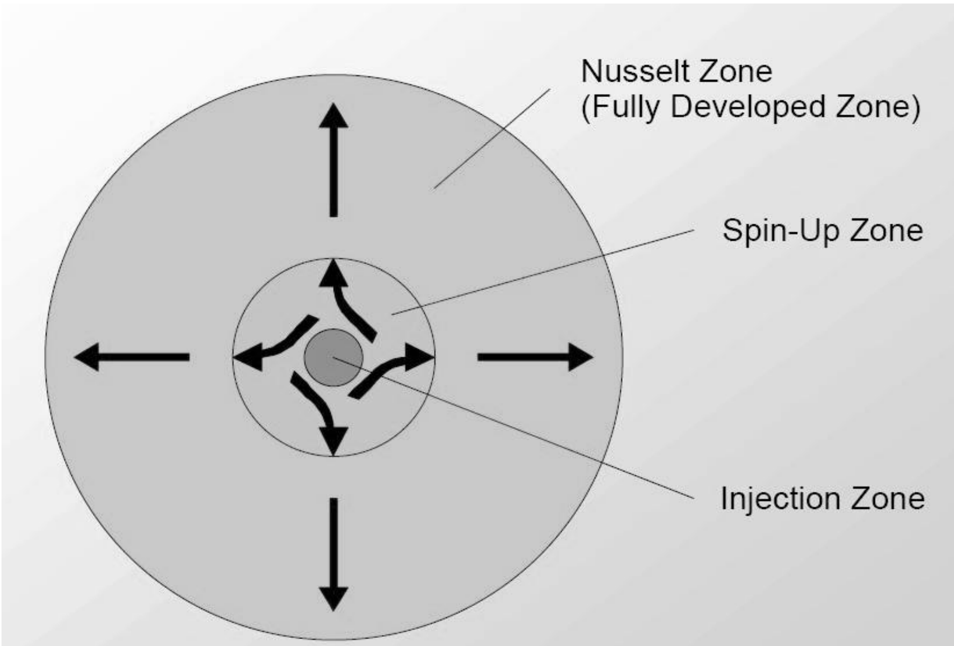

Figure 1.5: Top view of the spinning disk that shows the motion relative to the spinning disk (Burns *et al.*, 2003).

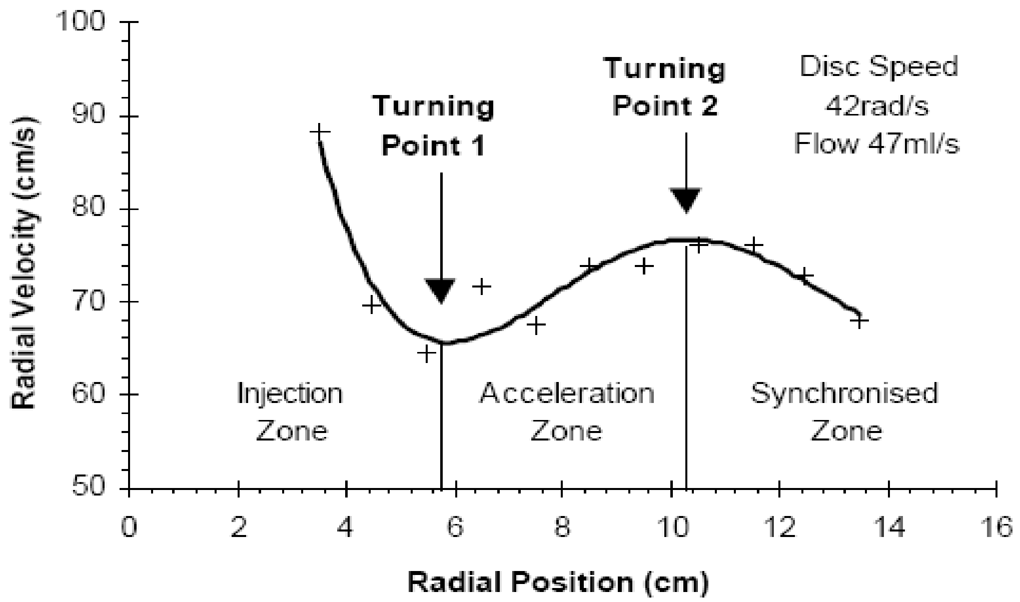

Figure 1.6: Radial velocity profile across the disk surface for a fluid. A polynomial fit was used to highlight the trend (Burns *et al.*, 2003).

1.2 Problem Statement

The previous studies about spinning disk technology by Oxley *et al*. (2000) and Boodhoo and Jachuck (2000) have showed that the fluid dynamics with highly sheared films on spinning surface results in significant enhancement of heat and mass transfer. It is also expected that a flow behavior using spinning disk technology not only offered the short liquid residence time but also rapid mixing in the liquid film.

Many experimental works (Burns *et al.*, 2003; Leshev and Peev, 2003; Ozar *et al.*, 2003; Basu and Cetegen, 2006 and Sisoev *et al.*, 2003) and modeling efforts

(Emslie *et al.*, 1958; Matsumoto *et al.*, 1973; Naletova *et al.*, 1995; Lingwood, 1996; Auone and Ramshaw, 1999; Matar and Lawrence, 2006; and Peev *et al.*, 2006) have been done to represent the hydrodynamics of thin liquids film flow over a spinning disk. However, the previous studies mostly focused only on the correlations between thin liquid film thickness and disk rotational speed. There is no extensive study to determine and describe the mixing characteristics of thin liquid film over a spinning disk.

Therefore, the hydrodynamics study and mechanistic model in this study was consists of correlation between mixing performance parameter, thin liquid film thickness and disk rotational speed that crucial to represent the mixing characteristics in thin liquid film flow over a spinning disk.

1.3 Research Objectives

The objectives of this research are:

a) To develop a mechanistic model that incorporated with mass and momentum conservation and mixing characteristics parameter for a thin liquid film flowing over horizontal spinning disk.

b) To perform the CFD simulation of thin liquid films flowing over horizontal spinning disk including formation of the flow waves, film thickness and mixing characteristics.

c) To design and fabricate the spinning disk test rig in order to validate the developed mechanistic model.

1.4 Scopes of Study

In this work, a mechanistic model is developed to show the correlation between mixing performances and thin liquid film thickness towards the effect of various disk rotational speeds and fluid velocity inlets. The governing equations for the model are based on Navier Stokes equation of incompressible flow and convective diffusion equation for thin film thickness prediction and mixing characteristics in thin film respectively.

For the thin liquid film thickness prediction, cylindrical coordinate system is used to model the axisymmetric flow of the liquid where the liquid is supplied at the center of the disk. The analysis only involved with the thin liquid film thickness across the horizontal surface of the disk. Thus, only the conservation of momentum equations in radial coordinate are considered here. Meanwhile, in order to describe the mixing in the axisymmetric thin liquid film flow, a two dimensional coordinate systems are taken into consideration in this work. Thus, in this analysis only the concentrations along the various radii of horizontal spinning disk are considered. Once the structure of the model was defined, scaling analysis technique was implemented to simplify and parameterize the governing equations. After that, all the governing equations were solved numerically by using finite different method in two dimension configuration.

In order to compare and validate the mechanistic model, experimental work and hydrodynamics model simulation in CFD are performed. Experimental work was carried out in spinning disk test rig with various disk rotational speeds. The thin liquid film thickness measurement based on the analysis of electrical resistance technique is performed to obtain the value of thin liquid film thickness over spinning disk. Further, mixing characteristics study of the thin liquid film is performed by visual observation of dye tracer distribution over the disk surface and then it is captured by a digital camera.

Then, the CFD commercial software package FLUENT® 6.3 is used to perform the simulation of thin liquid film flows over a horizontal spinning disk. For thin film thickness determination in CFD, boundary layer technique is used to observe the thin liquid film over the horizontal disk. Furthermore, a large number of the inert particles are released into the flow domain to simulate the dye tracer distribution over the spinning disk to study the details of mixing characteristics of the thin liquid film in CFD.

Finally, the model validation and comparison is carried out to prove that the developed mechanistic model and CFD model are capable of representing the thin liquid film flow over a horizontal spinning disk surface.

1.5 Thesis Organization

This thesis consists of five chapters as follows:

Chapter 1 describes the general knowledge about the process intensification (PI), spinning disk reactor (SDR) and hydrodynamics of thin liquid films over a horizontal spinning disk. The problem statement, research objectives and scopes of study are highlighted clearly in this chapter.

Chapter 2 provides review related to definition of PI with some examples of its applications in chemical processing industries and experimental works reviewed. On top of that, description of mixing principle and a review on mathematical modeling from other researcher also presented in this chapter.

Chapter 3 provides the methodology that includes the development of mechanistic model, fabrication of spinning test rig and experimental works of thin liquid film flows over a horizontal spinning disk. Hydrodynamics modeling by using Fluent® 6.3, a commercial software package is also presented.

Chapter 4 presents the results and discussion section for this research. The first part provides results of mechanistic model at various rotational speeds, liquid velocity inlets and Reynolds numbers. Then, hydrodynamics study results from experimental works and hydrodynamics modeling using Fluent® 6.3 including liquid thin film thickness and mixing characteristics are presented in the following part. Final part in this chapter describes the model validation and comparison between mechanistic model, CFD model and experimental data comprehensively.

Chapter 5 presents the concluding remarks of this research project. Despite that, some recommendations are highlighted as well for further improvements in the hydrodynamics study of thin liquid film flows over a horizontal spinning disk.

CHAPTER 2

LITERATURE REVIEW

Review on the definition of process intensification (PI) and its potential in chemical processing industries is described in this chapter. Works on spinning disk reactor (SDR) as one of the process-intensifying equipment is described with some examples of its applications and experimental works reviewed. In addition, the liquid mixing principle is highlighted and reviews on mathematical modeling for thin liquid film flow from other researchers are also presented in this chapter.

2.1 Process Intensification

Over the last few decades, a number of different definitions of PI have been used and published. Ramshaw (1995), one of the pioneers in this field, defined PI as a strategy for making dramatic reduction in the size of chemical plant needed to achieve a given production objective. These enviable objectives may be achieved provided the size of individual plant items can be radically reduced to 100 fold or more in volume. The definition is rather narrow, describing PI exclusively in terms of the reduction in plant or equipment size which is one of the several possible desired effects of PI. On the other hand, according to Stankiewicz and Moulijn (2000) and Stankiewicz and Drinkenburg (2004), PI is defined as novel equipment, processing techniques and process development methods that, compared to conventional ones, offer substantial improvements in (bio) chemical manufacturing and processing as well as an extensive description of a PI toolbox, that involved two dimensions of PI: equipment and processing methods.

Meanwhile, the BHR Group (2003) describes PI as a revolutionary approach to process and plant design, development and implementation. Providing a chemical process with the precise environment it needs to flourish which will results in better products, and processes which are safer, cleaner, smaller and cheaper. PI does not just replace old, inefficient plant with new, intensified equipment. It can challenge business models, opening up opportunities for new patentable products and process chemistry and change to just-in-time or distributed manufacture.

All the definitions above only restrict PI to engineering methods and equipment. It stated clearly that the development of a new chemical route or the change in composition of a catalyst, no matter how dramatic the improvements they bring to existing technology, do not qualify as PI. Then, Stankiewicz and Mouljin (2000) proposed the definition of PI in a shorter and concise form: "Any chemical engineering development that leads to a substantially smaller, cleaner and more energy-efficient technology is process intensification".

PI is a rapidly developing field that has already inspired many ideas in modeling and design of new equipment and operating modes, and whose potential is by far not fully tapped. The apparent benefits of this technology are many and it promises impressive improvements in process plants. Miniaturization or size reduction is a hallmark of PI, thus process equipment reduction generally improves inherent safety by reducing both the quantity of hazardous material that can be released in case of loss of containment, and the potential energy contained in the equipment. This energy may be from high temperature, high pressure, or heat of reaction. Therefore, it can dramatically boost the plant operation efficiency by change away from batch processing to continuous processing method. Especially in the case of extremely exothermic reactions whereby the heat can be removed continuously as it is being released (Jachuck, 2002).

While cost reduction was the original aim of PI, there were other important benefits in aspect of improved energy efficiency. The use of PI technique such as energy source in centrifugal fields will lead to significant energy saving as presented by Jachuck *et al.* (1997). In the work, they observed that polymerization of styrene managed to achieve a considerable reduction in reaction times on a spinning disk even if the reaction temperature is unchanged. It is expected that a spinning disk reactor using a multi-disk system may result in up to 40% energy saving in comparison to a conventional batch reactor.

Moreover, there were others benefits of PI technology that included: process flexibility, improved product quality, speed to market, just in time manufacturing, reduced foot print and distributed manufacturing capability. Oxley *et al.* (2000) found that this intensified system could offer reduction in reaction time, reduction in inventory and also reduction in impurity level.

2.2 Spinning Disk Reactor (SDR)

Stankiewicz and Moulijn (2000) have specified that PI can be divided into two areas, process-intensifying equipment and process-intensifying methods. Apparently, there can be some overlap where new methods may require novel types of equipment to be developed and vice versa. Thus, spinning disk reactor (SDR) was categorized as one of the process-intensifying equipment that exploits the centrifugal field as an energy source (process-intensifying methods), to produce thin highly sheared film on disk surface due to radial acceleration. SDR is depending on high centrifugal acceleration over a disk surface to overcome interfacial mass transfer limitations that cannot be achieved in conventional unit. It also provides plug flow and intense mixing while resisting fouling. Furthermore, very thin films are generated, typically in fractions of a millimeter down to a few microns thick, through controlled flow rate. The disk rotational speed can deliver surface to volume ratios tailored to processing requirements, ranging from 1000s of m^2/m^3 for high viscosity materials such as polymer melts, down to 100000s of m^2/m^3 for low viscosity systems typical of a wide range of chemical synthesis routes. SDR has a short residence time typically 0.1 s and overall heat transfer coefficient could achieve as high as $10kW/m^2K$ (Protensive, 2000).

The short residence time in SDR and the capabilities to eliminate the problem of mass and heat transfer limitations in conventional units, leads to the feasibility of processing foodstuff in food industry. As stated by Protensive (2000), SDR can be useful in sugar refining process. This process can be particularly energy vigorous to concentrate sugar from solution; it required multiple effect evaporation units.

Furthermore, the viscosity of sugar solution will gradually increase as water is continually removed from this liquor; this made it difficult to process. By using SDR, the rapid spinning disk centrifugally accelerating the viscous liquid film and heating it to the correct temperature with right amount of heat input and allows for rapid evaporation of water from the liquor. An experiment are performed in SDR Type-100 series by Protensive and 25.6% mass concentration of sucrose solution as a feedstock, then it was possible to concentrate the solution up to 61% mass concentration of sucrose in a single pass across the disk. This SDR with 10 cm diameter disk was able to produce 21 kg/day of concentrated sugar liquor.

Meanwhile, there are also numbers of experimental works performed by previous researcher to proof the distinct characteristic of SDR than other conventional batch units. Boodhoo and Jachuck (2000) developed a compact thin film reactor for continuous processing of free radical polymerization. They observed that significant reduction in processing times can be achieved due to the superior heat and mass transfer characteristics of the SDR. The equivalent batch time needed to reach the 80% product conversion was obtained in 50 minutes in the SDR as compared to 130 minutes in a batch reactor. In addition, SDR allowed rapid mixing in the liquid film even when viscosities of the polymers are high. This is due to the effect of disk rotational speed promotes very high of polymerization. The SDR also introduces an additional parameter that is the rotational speed which can be used to control the reaction rate and therefore enhanced the quality of the product with tight molecular weight distribution. Hence, a SDR can be used to intensify the free radical polymerization of styrene.

The kinetics study of free radical polymerization on SDR has been done by Leveson *et al.* (2003). A numerical simulation is performed to investigate how reduced rates of termination would influence time conversion behavior of free radical styrene polymerization. Comparison is made between model predictions and experimental data. Theoretical model is developed to calculate propagation rates in the absence of termination reactions. Then, a series of experiments using online Fourier transform infrared spectroscopy (FTIR) and Raman techniques are used to measure radial conversion profile from the SDR. They observed that the spinning disk surface of SDR promotes extension of the polymer chain whereby can prevent the propagating chains from terminating through bimolecular reactions. The good agreement between predicted model and experimental results showed strong evidence that the hydrodynamics regime created on surface of a SDR can lead to reduced rates of bimolecular termination.

2.3 Hydrodynamics of Thin Liquid Films

2.3.1 Experimental Work

The flow of a thin liquid film over spinning disk has many applications in practice. Controlling the disk rotational speed will influence the formation of liquid thin film surface waves over horizontal spinning disk (Sisoev *et al.*, 2003). Thus, it will offer the possibility of controlling transport rates in the liquid thin film in SDR. Early experimental investigations of fluid flow over a spinning disk have observed different wave regimes in film over a spinning disk. Matsumoto *et al.* (1973) demonstrated that high flow rate leads to appearing spiral waves that move from the disk center to the disk periphery was formed. Lingwood (1996) also observed that formation of circumferential waves moving from the disk center to the disk periphery at moderately higher flow rate. Furthermore, Auone and Ramshaw (1999) demonstrated that a small flow rate formed a smooth liquid thin film over the disk.

Leshev and Peev (2002) have investigated film flow of water and two aqueous solutions on horizontal rotating disk. Various film thicknesses along the disk radius at different volumetric flow rates and speeds rotation are obtained. It has been established that when the centrifugal forces are dominant, the thickness decreases continuously with radius location from the center to the edge of the disk and can be predicted by the equation of Lepehin and Riabchuk (1975) which accounts for the Coriolis force. At low speeds of revolution a hydraulic jump is present. Its position depends on the density, dynamic viscosity and surface tension of the liquid, its volumetric flow rate and the speed of rotation.

Experiments on characterization of thin liquid films flowing over stationary and rotating disk surfaces are described by Ozar *et al.* (2003). In the case of rotation, the liquid film inertia and friction influenced the inner region where the film thickness progressively increased. Then, the outer region where the film thickness decreased was primarily affected by the centrifugal forces. They also performed a flow visualization study of the thin film in order to determine the characteristics of the waves on the free surface. At high rotational speeds, spiral waves were observed on the liquid film. It was also determined that the angle of the waves which form on the liquid surface was a function of the ratio of local radial to tangential velocity.

The experimental investigations of flow over a spinning disk have attempted to measure the local maximal of the local mean film thickness, therefore real-time and rapid measurement are required to make sure the measurement value can be obtained precisely. Previous studies have presented various techniques for determination of the film thickness: needle probe method (Espig *et al.*, 1965 and Matsumoto *et al.*, 1973), infrared absorption (Charwat *et al.*, 1972), capacitance sensor (Thomas *et al.*, 1991), laser light reflection technique (Ozar *et al.*, 2003) and electrical resistance technique (Burns *et al.*, 2003).

Burns *et al.* (2003) have demonstrated a method of rapid measurement of liquid film thickness on a spinning disk surface by using electrical resistance technique. This technique based on the analysis of the electrical resistance of the liquid film and its relationship to film thickness when high frequency voltages are applied. The spinning disk surface used for this study was embedded with twelve brass rings that act as an electrode at radial intervals position. The top of the disk was milled and polished to produce a smooth continuous surface. This experimental work with electrical resistance technique has proved as a useful tool for macroscopic film thickness measurement.

Electrical resistance technique in the measurement of liquid volumes has been used in variety of applications. Work by Basic and Dudukovic (1995) applied this technique to a rotating packed bed to get real-time measurements of liquid hold-up within the bed, and to estimate the degree of anisotropy of liquid distribution. The measurement was taken across the whole of the packed bed to give a single total volume measurement. Later, study by Burns *et al.* (2000) adapted this technique to determine liquid hold-up and residence time for a gas-liquid system, within different radial zones inside a rotating packed bed. The results were compared with predictions based on established flow models have a good agreement. The relationship between gas flow rate and rotational speed during flooding was discussed and compared for low and high porosity packing.

These works have formed the foundation of the electrical resistance technique applied to liquids thin film flow over a spinning disk. Moreover, electrical resistance technique can provide a rapid method of obtaining liquid film thickness measurement during operation. The most importantly, this technique is more practical and economical than other techniques.

2.3.2 Modeling of Thin Liquid Film

Experimental works on SDR mostly are directed at proving the feasibility of concepts and ideas of PI and establishing the key design parameter of various intensified process system units. Further, Aoune and Ramshaw (1999) mentioned that a generalized fluid dynamic model of the flow of liquid films over rotating surfaces is highly desirable as it would provide a firm basis for further development of this spinning disk technology especially in process control and monitoring for this intensified system. Thus, mathematical modeling of film flows over a spinning disk was presented by Sisoev *et al.* (2003). An inherent property of this flow is the formation of waves, whose amplitude may have the same scale as the film thickness. Computed non-linear waves of the second family of solutions of the Shkadov model, which describes the falling film problem, were used to model the waves that accompany the flow over a rotating disk at large Eckman number. Eckman number, E is the ratio of viscous force to Coriolis force and defined as:

$$E = \frac{\upsilon}{H_c^{\,2}\Omega} \tag{2.1}$$

where υ denoted as the liquid viscosity, H_c as dimensionless length scale and Ω represent the disk rotational speed.

As a matter of fact, the original mathematical model of fluid flow spreads on a horizontal spinning disk was presented by Emslie *et al.* (1958). The mathematical model employs lubrication theory and results in a balance between the viscous resistance of the fluid and the centrifugal force. It provides a simple relation between fluid flux and the film thickness. Later, the function of the Coriolis force has been investigated intensively by Momoniat and Mason (1997). It extends the equation presented by Emslie *et al.* (1958) and reformulated it to include the Coriolis force term. The problem is formulated as a Cauchy intial-value problem. The numerical solutions that obtained by integrating along its characteristic curves, are compared with analytical solutions of the equation by Emslie *et al.* (1958) to determine the effect of Coriolis force.

Basu and Cetegen (2006) presented an integral analysis of hydrodynamics and heat transfer in a thin liquid film flowing over a rotating disk surface, for both constant temperature and constant heat flux boundary conditions. The governing