UNIVERSITI PUTRA MALAYSIA

IMPROVING PETROLEUM LIQUID FLOW IN A ROTATING DISK APPARATUS USING STRUCTURED INNER SURFACES AND POLYMERIC ADDITIVES

MUSAAB KADEM RASHED

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By

MUSAAB KADEM RASHED

Thesis Submitted to the School of Graduated Studies, Universiti Putra Malaysia in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

December 2017

DEDICATIONS

To

The Memory of My Dear Parents,

Mr. Kadem Rashed Khalaf

Mrs. Kameela Hameed Khalaf

May They Rest in Peace

To

My Marvellous Family

In Recognition of their Worth, Love, and Respect

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirements for the degree of Doctor of Philosophy

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Chairman : Associate Professor Mohamad Amran Bin Mohd Salleh, PhD
Faculty : Engineering

The most economically feasible technique to transport petroleum products such as crude oil and its derivatives is transporting liquids through commercial pipelines. Liquid transportation through pipelines is considered as one of the major energy-consuming phenomenon in the industry due to turbulence within the fluid. As turbulence increases, it reduces the initial flow rate at which liquids can be pumped. As a remedy to encourage continuous flow of liquid at the prevailing flow rates, a large number of scientists have suggested different passive, active and even interactive techniques to overcome this problem. Recently there have been a growing interest to use the rotating disk in numerous industrial application such as rotating mixing, rotating disk reactor, steam turbines, gas turbines, pumps, and other rotating fluid machines. However, these applications have been considered as energy consuming regimes.

In the present work, a high precision rotating disk apparatus (RDA) was designed, fabricated, and used to investigate the turbulent drag reduction characterisation of diesel fuel. The experimental work of this study was divided into three main stages. The first stage was passive drag reduction. In this stage, a number of disks with four riblets types (L, U, RAT and SV- groove) and twelve different dimensions for each type were used. All experiments were performed at rotational disk velocities ranging from 2000 to 3000 rpm, which correspond to a Reynolds number (Re) range of (3.02×10^5- 4.53×10^5). The second stage was active drag reduction, which involved using different types of additives with a smooth disk only. A cationic polymer of polyisobutylene (PIB) and two anionic surfactants of sodium di-octyl sulphosuccinate (SDS) and sodium lauryl ether sulphate (SLES) were used as drag reducing agents. These additives were tested individually and as two complex mixtures of PIB-SDS and PIB-SLES. Polymer solutions were prepared in 50, 100, 150, 200, and 300 ppm, while the surfactant solutions were 200, 400, 600, 800, and 1000 ppm. The last stage in this work was the combination of passive and active drag reduction methods by using the same drag reducing agents that were used in the active stage with various structured disks.

From the passive results, it was observed that the drag reduction performance increased with decreasing riblets height and it decreased with rotational velocity. The maximum passive drag reduction achieved was 8.048 % for the SV-groove with a riblets height of 900 µm, while it was 0.975 %, 2.683 %, and 6.829 % for the L, RAT, and U-groove, respectively. In contrast, the active results showed a higher drag reduction compared to the passive results. The drag reduction increased with polyisobutylene concentration until a critical value at which the maximum drag reduction was achieved. The same behaviour was also observed for the two types of surfactant and the two complex mixtures. The highest drag reductions for PIB, SDS, and SLES with the smooth disk were 19.197 %, 8.03 %, and 13.8 %, respectively at a polymer concentration of 150 ppm and a surfactant concentration of 1000 ppm. However, the drag reduction percentage (%DR) of the complex mixtures was higher than their individual results, whereby the maximum %DR of PIB-SDS and PIB-SLES with the smooth disk was 25.7 % and 25.35 %, respectively.

The passive-active interactive results showed the same additive behaviour with all riblets types, whereby the drag reduction increased with additive concentration. However, the maximum drag reduction was achieved with high riblets dimensions (H=3100 µm) with all additive types. Moreover, the drag reduction values of the smooth disk were higher than that of all the structured disks with a height of 900 µm. Overall, a 26.93 % DR was achieved in this study for the complex mixture of PIB (150 ppm) and SLES (1000 ppm) using the SV-groove with a height of 3100 µm.

Finally, a computational fluid dynamics simulation using commercial ANSYS, CFX code was employed in order to explain the real mechanism of the riblets drag reduction. The simulation results clearly explained the drag reduction mechanism by the riblets, as well as providing good agreement between the simulation and observed experimental results.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENAMBAHBAIKAN ALIRAN CECAIR PETROLEUM DI DALAM ALAT CAKERA BERPUTAR MENGGUNAKAN PERMUKAAN DALAMAN BERSTRUKTUR DAN ADITIF POLIMERIK

Oleh

MUSAAB KADEM RASHED

Disember 2017

Pengerusi : Profesor Madya Mohamad Amran Bin Mohd Salleh, PhD
Fakulti : Kejuruteraan

Teknik yang paling menjimatkan untuk pengangkutan produk petroleum, seperti minyak mentah dan terbitan-terbitannya, di dalam industri adalah dengan memindahkan cecair tersebut melalui saluran paip komersial. Pengangkutan cecair di dalam saluran paip dianggap sebagai salah satu fenomena yang memerlukan tenaga yang banyak. Apabila aliran gelora meningkat, ia mengurangkan kadar aliran awal semasa cecair sedang dipam. Sebagai penyelesaian untuk aliran cecair yang berterusan pada kadar aliran semasa, sejumlah besar saintis mencadangkan pelbagai teknik pasif, aktif dan interaktif yang berbeza untuk mengatasi masalah ini. Kebelakangan ini pengunaan cakera berputar semakin menarik perhatian dalam pelbagai aplikasi industri seperti pengadun berputar, reaktor cakera berputar, turbin wap, turbin gas, pam, dan mesin-mesin cecair berputar yang lain. Walau bagaimanapun, aplikasi ini dianggap sebagai rejim yang memerlukan tenaga.

Dalam kajian ini, alat cakera berputar (RDA) berkejituan tinggi telah direka dan digunakan untuk menyiasat ciri-ciri pengurangan seret gelora bagi bahan api diesel. Kerja-kerja ujikaji di dalam kajian ini dibahagikan kepada tiga peringkat utama. Peringkat pertama adalah pengurangan seret pasif. Pada peringkat ini, beberapa cakera dengan empat jenis riblet (L, U, RAT dan SV-groove) dan dua belas dimensi yang berbeza untuk setiap jenis cakera telah digunakan. Kesemua ujikaji dilakukan pada kelajuan putaran cakera antara 2000 hingga 3000 putaran perminit (rpm), yang sepadan dengan julat nombor Reynolds (Re) (3.02×10^5- 4.53×10^5). Peringkat kedua ialah pengurangan seret aktif yang melibatkan penggunaan beberapa jenis aditif yang berbeza dengan menggunakan cakera rata sahaja. Polimer kationik polyisobutylene (PIB) dan dua surfaktan anionik natrium di-oktil sulfosuccinat (SDS) dan natrium lauril eter sulfat (SLES) digunakan sebagai agen pengurangan seret.

Aditif-aditif ini diuji secara individu dan campuran kompleks PIB-SDS dan PIB-SLES. Larutan polimer disediakan dalam kepekatan 50, 100, 150, 200, dan 300 bahagian per juta (ppm), manakala larutan surfaktan pula adalah 200, 400, 600, 800, dan 1000 bahagian per juta (ppm). Peringkat terakhir dalam kajian ini adalah gabungan kaedah pengurangan seret pasif dan aktif dengan menggunakan aditif yang sama yang digunakan pada ujikaji aktif dengan pelbagai cakera berstruktur.

Dari hasil ujikaji pasif, dapat dilihat bahawa prestasi pengurangan seretan meningkat dengan penurunan ketinggian riblet, dan menurun dengan peningkatan halaju putaran. Pengurangan seret maksimum yang dicapai adalah 8.048% untuk SV-groove dengan ketinggian riblet 900 μm, manakala masing-masing 0.975%, 2.683% dan 6.829% untuk L, RAT, dan U-groove. Sebaliknya, keputusan aktif menunjukkan pengurangan seretan yang lebih tinggi berbanding pasif. Pengurangan seretan meningkat dengan kepekatan polyisobutylene hingga nilai kritikal di mana pengurangan seret maksimum dicapai. Tingkah laku yang sama juga diperhatikan untuk kedua-dua jenis surfaktan dan dua campuran kompleks. Pengurangan seret tertinggi PIB, SDS, dan SLES dengan cakera rata ialah 19.197%, 8.03%, dan 13.8%, masing-masing pada kepekatan polimer 150 ppm dan kepekatan surfaktan 1000 ppm. Walau bagaimanapun, peratusan pengurangan seret (% DR) campuran kompleks adalah lebih tinggi dari aditif individu, di mana maksimum DR% PIB-SDS dan PIB-SLES dengan cakera halus ialah 21.46% dan 25.35%.

Hasil ujikaji interaktif aktif pasif menunjukkan tingkah laku aditif yang sama bagi semua jenis riblet, di mana pengurangan seret meningkat dengan kepekatan aditif. Walau bagaimanapun, pengurangan seret maksimum boleh dicapai dengan dimensi riblet yang tinggi (H = 3100 μm) untuk semua jenis aditif. Selain itu, nilai pengurangan seret cakera rata adalah lebih tinggi daripada cakera berstruktur dengan ketinggian riblet 900 μm. Secara keseluruhannya, kira-kira 26.93 %DR dicapai dalam kajian ini untuk campuran kompleks PIB (150 ppm) dan SLES (1000 ppm) menggunakan SV-groove dengan ketinggian riblet 3100 μm.

Akhir sekali, simulasi pengiraan dinamik bendalir menggunakan kod komersial ANSYS CFX digunakan untuk menjelaskan mekanisme sebenar pengurangan seret oleh riblet. Hasil simulasi menerangkan mekanisme pengurangan seret oleh riblet dengan jelas, dan kesetaraan yang baik antara hasil ujikaji dan simulasi dapat diperhatikan.

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I certify that a Thesis Examination Committee has met on 14 December 2017 to conduct the final examination of Musaab Kadem Rashed on his thesis entitled "Improving Petroleum Liquid Flow in a Rotating Disk Apparatus using Structured Inner Surfaces and Polymeric Additives" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

Members of the Thesis Examination Committee were as follows:

Suraya binti Abdul Rashid, PhD11
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Thomas Choong Shean Yaw, PhD
Professor Ir.
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Luqman Chuah Abdullah, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Mohsen Sharifur, PhD
Senior Lecturer Pr. Eng.
University of Pretoria
South Africa
(External Examiner)

NOR AINI AB. SHUKOR, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 29 January 2018

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Mohamad Amran Bin Mohd Salleh, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Mohd Halim Shah Bin Ismail, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Hayder A. Abdul Bari, PhD
Professor
Center of Excellence for Advanced Research in Fluid Flow
Universiti Malaysia Pahang
(Member)

ROBIAH BINTI YUNUS, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

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Name and Matric No.: Musaab Kadem Rashed (GS38826)

Declaration by Members of supervisory Committee

This is to confirm that:

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ASSOC. PROF. DR. MOHAMAD AMRAN MOHD SALLEH
Head
Dept of Chemical & Environmental Engineering
Faculty of Engineering
Universiti Putra Malaysia
43400 Serdang, Selangor

Signature: ______________________
Name of Chairman of Supervisory Committee: Associate Professor Dr. Mohamad Amran Bin Mohd Salleh

DR. MOHD HALIM SHAH ISMAIL CEng. MIChemE
Associate Professor
Department of Chemical & Environmental Engineering
Faculty of Engineering
Universiti Putra Malaysia

Signature: ______________________
Name of Member of Supervisory Committee: Associate Professor Dr. Mohd Halim Shah Bin Ismail

PROF. DR. HAYDER A. ABDULBARI
Professor
Faculty of Chemical & Natural Resources Engineering
Universiti Malaysia Pahang

Signature: ______________________
Name of Member of Supervisory Committee: Professor Dr. Hayder A. Abdul Bari

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%Dr	Drag reduction percentage
APG	Alkyl Polyglycoside
BLADEs	Boundary layer devices
CDMB	Cetyl dimethyl amino aciticacidbetaine
CFD	Computational fluid dynamics
CTAC	Cetyltrimethyl ammonium chloride
DNS	Direct Numerical Simulation
DR	Drag Reduction
DRAs	Drag Reducing Agents
GG	Guar gum
GPC	Gel permeation chromatography
HPAM	Hydrolysed polyacrylamide
HXG	Hydroxypropyl xanthan gum
I.D	Internal diameter
LDV	Laser Doppler Velocimetry
LEBUs	Large eddy breakup devices
LES	Large Eddy Simulation
MBPD	Million barrels per day
MIA	Mesh independency analysis
MMD	Mechanical Molecular Degradation
MW	Molecular weight
ODEAO	Oleyl di hydroxyethyl amine oxide
OLDs	Outer layer devices
OTAC	Octadecyltrimethylammonium chloride
PAA	Poly acrylic acid
PAM	polyacrylamide
PEO	polyethyleneoxide
PIB	Polyisobutylene
PIV	Particle Image Velocimetry
PS	Polystyrene
PVAm	Polyvinyl amine

RANS	Reynolds-averaged Navier–Stokes
RAT	Right Angle Triangular groove shape
RDA	Rotating Disk Apparatus
RDC	Rotating Disc Contactor
Re	Reynolds Number
SDR	Spinning Disk Reactor
SDS	Sodium Di-octyl Sulfosuccinate
SLES	Sodium lauryl ether sulfate
SST	Shear Stress Transport
SV	Space-V groove shape
TAPPMs	Tandem arrayed parallel plate manipulators
TAPS	Trans-Alaska Pipeline System
TEM	Transmission Electronic Microscopy
XG	Xanthan gum
ΔP	Pressure Drop (Pressure Different)

CHAPTER 1

INTRODUCTION

1.1 General Background

Turbulence is considered a power consuming phenomenon in many academic and industrial applications due to its chaotic nature. Such unwanted power consumption can massively affect the whole process itself, as additional power is needed to maintain the operation where the resistance to turbulent flow is called drag. Drag has been known as the main reason for energy loss in pipelines and other similar transportation channels due to turbulence within the flow and the friction between the flowing fluid and the pipe wall surfaces. These energy losses are shown as an increase in pressure drop, which will lead to consumption of greater pumping power (Abubakar et al., 2014; Camail et al., 1998; Hong et al., 2015; Khadom & Abdul-hadi, 2014; Shenoy, 1984).

The process for reducing drag is called a “drag reduction phenomena” in which the friction of a liquid flowing in a pipe in turbulent flow can be decreased. This can be achieved by altering the physical properties of the fluid (using a small amount of an additive) or by modifying the surface structure of the solid part (using a complaint wall, an oscillating wall, dimples, and riblets) (Li et al., 2008). This is of interest in airplane tank filling, field irrigation, flood water disposal, firefighting, water heating and cooling systems, suspensions and slurries, sewer systems, oil well operations, oil pipeline conduits, biomedical systems including blood flow, and marine systems (Brostow, 2008; Toms, 1949). Drag reduction was discovered in the early forties by Toms (1948). He studied the effect of a polymer added into a turbulent Newtonian fluid. He proved that the addition of small amount of polymer (in ppm) into the turbulent flow could produce a significant result in reducing frictional drag. Since then, drag reduction phenomena have attracted the attention of an enormous number of researchers due to its high level of academic and industrial impacts (Baron et al., 1993; Choi et al., 2000; VlRK, 1975; Zadrazil et al., 2012).

Generally, drag reduction (DR) can be classified into two major categories, namely, active and passive drag reduction. Active drag reduction methods utilise viscoelastic polymeric additives with minute additive concentrations to enhance the flow. For example, a tremendous 80 % flow enhancement has been observed in many cases. Apart from polymers, surfactants and even suspended solids are confirmed efficient and economically feasible drag reducing agents. Simply adding a minute amount of these additives is sufficient to reduce drag significantly, resulting in 20 % DR or more (Liaw, Zakin, & Patterson, 1971; Hoyt, 1972; Lumley, 1973; Lumley, 1969; VlRK, 1975; Christopher M White & Mungal, 2008).

The five most popular methods of passive DR involve the use of wavy and oscillating walls, dimples, microbubbles, compliant surfaces, and riblets. New passive methods such as the utilisation of thin lubricating films using air (Tokunaga et al., 2000) and water repellent surfaces (Watanabe et al., 2001) also exist but have not been investigated as comprehensively as the first five. Among all the passive means, it can be observed that the most efficient and interesting DR technique is the use of riblets. DR by riblets includes the use of longitudinal micro-grooves etched on a surface originally designed for skin friction reduction in a fully turbulent boundary layer (Kramer, 1960).

Despite all the advantages mentioned earlier, passive and active drag reduction techniques come with their own drawbacks. In active DR, the stability of long chained polymeric additives against high shear forces is considered as one of the major problems, where the polymer molecules tend to break when exposed to high shear rates, which is an irreversible phenomenon that can lead to the loss of drag reduction effectiveness. Such phenomena cannot be found in surfactant solutions where the surfactant micelles break easily when exposed to high shear rates but will reform after passing the high shear rate areas and regain their low drag reduction abilities (when compared to polymers). On the other hand, despite all the passive DR efforts, the DR produced using riblets is still low at around 10 % on average. This might be because of the dimensions and shape optimisation that limit exploring the real influence of such phenomena.

Indeed, several instruments have been used to examine turbulence DR such as in pipelines, wind tunnels, channels, and annular conduits. Recently, several studies have examined the DR of a flow by additives through other techniques, such as coaxial cylinders (Bizotto & Sabadini, 2008; Nakken, Tande et al., 2001), cylindrical double gap rheometer device (Kalashnikov, 1998), and rotating disk apparatus (RDA) (Choi et al., 1999; Choi & Jhon, 1996; Choi et al., 2000; Kim et al., 1999; Lim et al., 2002; Mccormick, Heater, Morgan, & Safieddine, 1990; McCormick et al., 1990; Peyser & Little, 1971; Rodriguez & Winding, 1959). The Rotating Disk Apparatus (RDA) used in DR applications is equipment for simulating external flow which involves the flow over flat plates, in addition to the flow around submerged objects and is used for turbulence DR characterisation (Tong et al., 1990).

The rotating disk is a popular geometry for studying different flows, because of its simplicity and the fact that it represents a classical fluid dynamics problem. It is a subject of widespread practical interest in connection with steam turbines, gas turbines, pumps, and other rotating fluid machines. In addition, the high-speed rotational flows are found in numerous industrial applications, for example oil refinery, sewage treatment plants, cement industry, food industry, and paper industry. However, these flows often consume a great deal of energy (Owen & Rogers, 1992; Said et al., 2015).

1.2 Problem Statement

Reducing friction power losses during turbulent liquid flow in pipes, conduits, mixing systems or any other chemical engineering application has been the aim of all the drag reduction research efforts over the past few decades. Laminar flow is rarely found in industry, and the turbulent mode of flow is dominant. Turbulence generation in a controlled media is considered positive in most heat and mass transfer systems. On the other hand, turbulence generation requires high shear rates and that can lead to higher friction resistance. Overcoming the shear resistance has been extensively investigated for turbulent flow in pipes, channels, and a wind tunnel, where passive and active techniques have been introduced and employed. In some cases, interactive drag reduction methods were investigated where the integrated effect of additives and surface modification were studied. In addition, DR studies using an RDA have gradually taken place, and such studies have become increasingly important due to applications in mixing, rotating reactors, etc. Data is still limited in this area of study.

The passive DR technique is considered a permanent solution where no continuous resources consumption is required as in active drag reduction methods. However, this technique does not show high drag reduction performance when compared to active techniques due to the low interaction area with the turbulence core. All previously investigated passive drag reduction designs have been conducted in pipes and straight channels and directed mainly to certain drag reduction applications such as marine and submerged surfaces, while there are an enormous number of industrial applications that face the same friction problem such as rotating disk mixers that have seen no passive drag reduction research effort conducted to date. All previous works on rotating disk apparatus include a smooth disk with different additive types (Akindoyo & Abdulbari, 2016; Choi et al., 2000; Hong et al., 2008; Hong et al., 2015; Kim et al., 1998; Sung et al., 2004; Sung et al.,). In this investigation, no reference was found for RDA with modified surfaces.

Active drag reduction methods utilise different viscoelastic additives, such as polymers, surfactants and suspended solids, with minute additive concentrations to enhance the flow. The use of these Drag Reducing Additives (DRAs) in a water solvent is well known and has been widely investigated (Choi & Jhon, 1996; Ge et al., 2007; Hong et al., 2008; Hong, Choi, et al., 2015; Kim et al., 2000; Kim et al., 2011; Vatankhah et al., 2011; Zhang et al., 2011), but very little has been reported for comparable additives for oily fluids.

It is believed that interactive drag reduction methods can introduce an enhanced technique that can overcome many of the previous drag reduction drawbacks. The word ‘interactive’ can arise through combining two or more active drag reducing additives or by combining these additives and their complexes with passive drag reduction structures such as riblets or dimples. Such complex interactive drag reduction method has not been properly investigated to date, especially in an enclosed flow system such as RDA.

The coherent turbulence structures that develop over grooved riblets have various features that are not yet sufficiently understood. Computational Fluid Dynamic (CFD) is one of the tools that can be used to study turbulent flow behaviour. Most previous studies of the CFD simulation of a rotating disk system have focused on a rotating disk mixer, a spinning rotating reactor, and a rotating contactor, while the numerical studies of DR by use of riblets have been conducted in water channels, on a flat pate, and in a wind tunnel. To the knowledge of the authors, there has not been a previous CFD simulation of passive DR using RDA. Therefore, there is a need to study the turbulence structure developed over riblets and to explain the passive drag reduction mechanism when using RDA by applying CFD simulation with ANSYS, CFX software. In the present work, all of the abovementioned problems will be addressed.

1.3 Objectives

Based on the research background and problem statement described in the previous section, the following lists the objectives of this research:

1- To investigate the drag reduction potential of different structured aluminium surfaces with diesel flow using RDA.
2- To evaluate the effects of the dimensions of the structures and designs on the diesel flow behaviour and drag reduction performance.
3- To investigate the active drag reduction effectiveness of additives as drag reducing agents for commercial diesel.
4- To investigate the effects of passive-active interactive drag reduction techniques for a diesel flow system.
5- To apply a reliable and validated computational fluid dynamics (CFD) model to explain and identify drag reduction in the passive mode.

1.4 Hypothesis

At the end of this study, it is expected that:

1. The structured disk surfaces with different types of riblets will show better DR performance than that of a smooth surface, where the turbulence would shift away from the riblets walls.
2. The riblets types, riblets heights, and spacing play a vital role on the turbulence and structure of the vortices in the boundary layer above the structured disks, and that will affect the DR efficiency of these riblets.
3. Using polymers and surfactant additives with diesel fuel will enhance its DR performance. The additive molecules interfere with the turbulent structures and reduce or suppress eddies thus formed inside the diesel solutions and thereby the DR performance is improved. In addition, the complex mixtures of these additives will show better DR performance than their individual results.
4. The poor drag reduction performance of the passive DR method can be improved by using the passive-active interactive drag reduction method.
5. A computational fluid dynamic simulation using ANSYS software can be used to investigate the velocity distribution and to visualise the turbulence structure or the formation of vortices above the structured surface disks and compare with the results of the smooth surface disk.

1.5 Scope of the Study

The following scope has been identified in order to achieve the objectives:

1. Diesel fuel is the main test fluid in this study, which is obtained from Shell Malaysia.
2. Forty-eight structured disks were fabricated using four different types of riblets or grooves (L, U, SV, and RAT – groove) with 12 varied dimensions for each type.
3. The torque readings for the smooth disk and structured disk in the rotary disk apparatus were collected to calculate the corresponding torque, followed by the percentage of the passive DR.
4. A cationic polymer (polyisobutylene) with a high molecular weight (MW) of 4.7×10^6 g/mol was employed to determine the significance of the effect on the turbulence DR in the rotary disk apparatus. Investigated polymer concentrations were 50, 100, 150, 200, and 300 ppm.
5. Two different types of surfactants, Sodium Di-octyl sulphosuccinate (SDS) and Sodium lauryl ether sulphate (SLES) with varied concentrations were included in the experiment to investigate their effects on the turbulence DR in the rotating disk apparatus. Investigated surfactant concentrations were 200, 400, 600, 800, and 1000 ppm.
6. The density and viscosity of the pure fluid was used to calculate the Reynolds Number (Re) of the fluid.
7. Two complex mixtures of PIB with Sodium Di-octyl sulphosuccinate (SDS) and PIB with sodium lauryl ether sulphate (SLES) were prepared and used to investigate the effect of the polymer-surfactant complex solution on DR performance using different concentrations of polymers and surfactants.
8. The rotational disk speed was varied from 2000 to 3000 rpm by 100 rpm intervals.

1.6 Rationale and Significance

Drag reduction is an alternative way to reduce pumping power losses during transportation of a fluid through pipelines. By injecting a drag reduction agent into a pipeline, the friction pressure losses in the pipeline can be decreased. The significance of this study is to discover a new system to reduce the turbulence drag, which is the main step to saving pumping power and eventually leading to cost saving. Furthermore, power saving is essential to cost saving in the plants.

The main contributions of this work are summarised below:

a. Passive DR with different riblets types and dimensions were experimentally investigated for the first time using RDA.
b. A high range of Reynolds number (3.02×10^5- 4.53×10^5) were utilised to study the effects of a high degree of turbulence on DR performance.
c. Hydrocarbon media fluid (diesel fuel) was employed using PIB and two types of surfactant.
d. Two novel complex mixtures of polymers and surfactants were used to improve the mechanical degradation resistance of PIB at a high range of Reynolds numbers.
e. A passive-active DR interaction technique was used to enhance the DR performance using soluble additives with the optimum type of riblets.
f. Further explanation of the real mechanism associated with the use of riblets in turbulent flows has been thoroughly explained using Computational Fluid Dynamics with ANSYS software.

1.7 Overview of the Study

This thesis comprises of five main chapters: Chapter 1 introduces the work. Chapter 2 discusses the relevant literature concerning passive and active DR, surfactants, polymers, complex mixtures, and previous work on computational fluid dynamics simulations. Chapter 3 explains the methodology, apparatus, and equipment used in the experimental work, as well as involves the simulation methodology using ANSYS, CFX software. Chapter 4 provides the experimental and simulation results, with an elaborated discussion of these results. Chapter 5 includes the conclusion and recommendations for further research. This thesis is accompanied by a list of references and relevant appendixes.

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