

**TWO PHASE FLOW OF WAXY CRUDE OIL-WATER IN HORIZONTAL
PIPES**

AHMAD SHAMSUL IZWAN BIN ISMAIL

UNIVERSITI TEKNOLOGI MALAYSIA

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AHMAD SHAMSUL IZWAN BIN ISMAIL

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~ All Praise Belongs to ALLAH S.W.T.~

This thesis is dedicated to

My Mother,

A strong and gentle soul who has taught me to trust in ALLAH S.W.T., believe in hard work that so much could be done with a little, and prays of day and night that have enable me to get such success and honor.

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ABSTRACT

Water produced along with the crude oil during production and transported together in a pipeline is a common occurrence in a petroleum production system. Understanding the behavior of crude oil-water flow in a pipe is crucial to many engineering applications, such as design and operation of flow lines and wells, separation systems, logs interpretations, and determination of the amount of free water in contact with the wall of the pipes that could render erosion or corrosion problems. Presently, there is no two phase flow study done on the Malaysian waxy crude oil-water. Therefore, a research work was conducted at the UTM-MPRC Institute for Oil and Gas, Universiti Teknologi Malaysia, to study the flow pattern, pressure drop, and water holdup of the Malaysian waxy crude oil-water flowing in a closed-loop system at an ambient condition through a 5.08 cm ID stainless steel horizontal pipeline. In the research work, water cuts were varied from 0% - 90% with mixture velocities ranging from 0.1 – 0.8 m/s. The research works comprised fluid characterization, flow pattern observation using a video camera camcorder, pressure drop, and liquid holdup measurement. Five flow patterns have been identified, namely stratified wavy flow, stratified wavy with semi dispersed flow at interface and oil film, dispersion of water in oil and oil continuous with emulsion, dispersion of oil in water with water continuous, and the newly found semi dispersed flow with semi emulsion at interface and thin oil film. The investigations proved that pressure drop was greatly influenced by flow pattern and mixture velocity. It was also found that the water holdup decreased slightly at higher water cuts due to the presence of emulsion in the crude oil – a great challenge when using a waxy crude oil in a two phase flow system. The experimental results could be used as a platform to understand better a more complex case of gas, oil, and water concurrent flow in a pipeline.

ABSTRAK

Pengeluaran air bersama-sama minyak mentah ketika pengeluaran dan penghantaran melalui talian paip telah menjadi kebiasaan bagi sistem pengeluaran petroleum. Kefahaman tentang perilaku aliran minyak mentah-air di dalam talian paip adalah penting untuk pelbagai aplikasi kejuruteraan, misalnya mereka bentuk dan pengoperasian talian aliran dan telaga, sistem pemisahan, pentafsiran log, dan penentuan jumlah air bebas yang bersentuh dengan dinding paip, yang boleh menimbulkan masalah pengaratan atau penghakisan. Sehingga kini masih tiada kajian dua fasa yang dilakukan terhadap minyak mentah Malaysia-air. Oleh itu, satu kajian telah dilaksanakan di UTM-MPRC Institut untuk Minyak dan Gas, Universiti Teknologi Malaysia, untuk mengkaji corak aliran, kejatuhan tekanan, dan air tertahan bagi aliran minyak mentah Malaysia-air di dalam sistem gelung tertutup melalui talian paip keluli mendatar yang berdiameter dalam 5.08 cm pada keadaan ambien. Dalam kajian ini, peratusan kenadungan air telah diubah dari 0 – 90% dengan halaju campuran dari 0.1 – 0.8 m/s. Kajian mencakupi pencirian cecair, penelitian corak aliran menggunakan perakam kamera video, dan pengukuran kejatuhan tekanan serta cecair tertahan. Lima corak aliran telah dikenal pasti, iaitu aliran berlapis berombak, aliran berlapis berombak dengan terselerak separuh di antara muka dan lapisan minyak, aliran air terselerak di dalam minyak dengan minyak berterusan bersama-sama emulsi, aliran minyak terselerak di dalam air dengan air berterusan, dan corak aliran yang baharu ditemui, iaitu aliran terselerak separuh dengan emulsi separuh di Antara muka dan lapisan minyak yang nipis. Kajian membuktikan bahawa kejatuhan tekanan amat dipengaruhi oleh corak aliran dan halaju campuran. Air tertahan didapati berkurang sedikit pada peratusan kandungan air yang tinggi kerana kehadiran emulsi dalam minyak mentah – suatu cabaran apabila menggunakan minyak mentah berlilin dalam sistem dua fasa. Hasil kajian ini boleh digunakan sebagai asas untuk memahami dengan lebih baik tentang kes yang lebih rumit, misalnya aliran gas, minyak, dan air secara bersama di dalam suatu talian paip.

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LIST OF ABBREVIATIONS

ASTM	: American Society for Testing and Materials
AMTEC	: Advance Membrane Technology Research Centre
Bb	: Bubbly Flow
CA	: Core Annular Flow
CA/OF	: Core Annular Flow with Oil Film
DAQ	: Data Acquisition
DSC	: Differential Scanning Calorimetry
DC	: Dual Continuous
DO	: Dispersion of Oil In Water With Water Continuous
DO/W&W	: Dispersion of Oil In Water Over A Water Layer
DW/O	: Dispersion Water in Oil
DW/O & O	: Dispersion Water in Oil and Oil Continuous
DO/W	: Dispersion Oil in Water
DO/W & W	: Dispersion Oil in Water and Water Continuous
DW/O & DO/W	: Dual type of dispersion
DWE	: Dispersion of Water In Oil and Emulsion
Dw-DP	: Water Continuous Dispersion with a Dense Packed Layer of Oil Droplets
Ew/o	: Water in Oil emulsion
Ew/o&w	: Water in Oil emulsion and Water Stratified Flow
w&Ew/o	: Water in Oil emulsion and semi water
Ew/o&D(Ew/o)/w	: Water in Oil emulsion and Water in Oil emulsion dispersed in Water Phase
EOR	: Enhanced Oil Recovery
FPSO	: Floating, Production, Storage, and Production
FPREE	: Faculty of Petroleum and Renewable Energy Engineering

GC-MS	: Gas Chromatography-Mass Spectrometry
HD	: High Definition
MPRC	: Malaysia Petroleum Resources Corporation
NI	: National Instrument
O/W	: Emulsion of Oil in Water
W/O	: Emulsion of Water in Oil
PETRONAS	: Petroliam Nasional Berhad
RPM	: Revolutions per minute
SKO	: Sarawak Oil and Gas Operation
SAJ	: Syarikat Air Johor
SOW	: Stratified Wavy
SOW&DO/W&OF	: Stratified Wavy with Dispersed Oil Droplets at Interface and Oil Film
SOW&DO/W	: Stratified Wavy with Dispersed Oil Droplets at Interface
ST	: Stratified flow
STW	: Stratified Wavy Flow
STSD&O	: Stratified Wavy with Semi Dispersed Flow at Interface and Oil Film
SDSE&TO	: Semi dispersed flow with semi emulsion at interface and thin oil film
ST&MI	: Stratified with Mixing at the Interface
TCOT	: Terengganu Crude Oil Terminal
UV	: Ultraviolet
UNIPEM	: Unit Perkhidmatan Makmal
UTM	: Universiti Teknologi Malaysia
WF	: Water Fraction
WAT	: Wax Appearance Temperature

LIST OF SYMBOLS

A_o	: Area of Oil (m^2)
A_w	: Area of water (m^2)
A	: Pipe Cross Sectional Area (m^2)
C	: Carbon
c	: Constant
cp	: Centipoise
C_w	: Water Fraction
C_o	: Oil Fraction
d	: Internal Diameter (m)
dp	: Pressure drop
dL	: Length of pressure drop
Eo	: Eötvös number
f_w	: Water fraction
f_m	: Mixture friction factor
g	: Gravity acceleration (m/s^2)
hp	: Horsepower
H_w	: Water Holdup
H_o	: Oil Holdup
H	: Holdup
H_{sw}	: No Slip Water Holdup
ID	: Internal Diameter (m)
L_e	: Entrance Length (m)
ΔL	: Differential distance
NR_e	: Reynolds number
N_{Fr}	: Froude number

NR_{em}	: Mixture Reynolds number
ΔP_{ow}	: Pressure drop during water flow (pa)
ΔP_{so}	: Pressure drop during oil flow (pa)
ΔP_t	: Pressure drop total (pa)
ΔP_m	: Measured differential pressure
P_o	: Pipe diameter occupied by oil, (m)
Pa.s	: Pascal second
P_c	: Pipe circumference, (m)
S_{ow}	: Interfacial perimeter (m)
S_o	: Oil wetted perimeters (m)
S_w	: Water wetted perimeters (m)
S_{ow}	: Interfacial perimeter (m)
S_I	: Superficial Interface
v	: Velocity (m/s)
V_m	: Mixture Velocity (m/s)
v_{so}	: Superficial Oil Velocity (m/s)
v_{sw}	: Superficial Water Velocity (m/s)
v_{sd}	: Superficial dispersed phase velocity (m/s)
v_{sc}	: Superficial continuous phase velocity (m/s)
v_t	: Volume of total liquid mixture of oil and water in pipe (m ³)
X	: Pressure drop factor based on single-phase flow of oil at total flowrate
%	: Percent
°	: Degree
°C	: Degree Celsius

Greek letters

β	: Inclination angle
σ	: Interfacial Tension (N/m)
ρ_m	: Mixture Density (kg/m ³)
ρ_o	: Density of Oil (kg/m ³)
ρ_w	: Density of Water (kg/m ³)
μ_o	: Oil Viscosity (Pa s)
μ_w	: Water viscosity (Pa s)
μ_c	: Continuous phase viscosity (Pa s)
μ_d	: Dispersed phase viscosity (Pa s)
ε_r	: Pipe wall roughness, (m)
ε_o	: Oil volume fraction
ε_w	: Water volume fraction
τ_o	: Wall shear in oil phase (N/m ²)
τ_w	: Wall shear in water phase (N/m ²)
τ_{ow}	: Interfacial shear (N/m ²)
τ	: Shear stress (D/cm ²)
$\dot{\gamma}$: Shear rate (1/sec)

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CHAPTER 1

INTRODUCTION

1.1 Background

The need for reliable experimental studies on many engineering applications of multiphase flow, such as in petroleum industry and petrochemical industry, has been the driving force behind an extensive research effort on the multiphase flow area especially in gas-liquid flow for many years ago. Among the earliest studies in the gas-liquid field were by Beggs and Brill (1973), Wicks and Dukler (1960), Hagedorn and Brown (1964), Gregory and Aziz (1975), and Cornish (1976). Recently, the industry has shifted its attention towards the understanding of the simultaneous flow of gas-oil-water mixtures (Atmaca *et al.*, 2008). Despite the extensive studies on gas-liquid two phase flow, there is a limiting case involves with liquid-liquid flow studies and still received inadequate attention. Due to the dwindling of conventional light crude oil or 'easy oil' reserves and existence of lots of matured oilfields around the globe, especially in the Malaysian oilfields, thus the phenomenon of concurrent flow of oil and water in pipelines has been the main subject of research studies in petroleum production and enhanced oil recovery with water injection. In some parts of the Malaysian oilfields operations' especially in the Sarawak oil and gas operation (which is also known as the SKO operation by Petronas), the oil and water are transported together to onshore via pipelines, after the released gas has been removed earlier using offshore facilities while the produced water is later separated using onshore separators. The SKO operation practises this

technique of transportation because it has been considered as a cost saving due to the close distance between the onshore facilities and offshore production platforms through pipelines connections. Furthermore, there are few occasions happened in the transportation lines where the water cuts could be as high as 90% but the wells are still considered economical to be operated (Ngan, 2010).

Theoretically, the liquid-liquid flow could be defined as the simultaneous flow of two immiscible liquids in a pipe. This phenomenon of two heterogeneous of liquid-liquid flow is common in the petroleum industry and also in the food, petrochemical and palm oil industries where in the petroleum fluids processing, the design of processing equipment and piping systems requires knowledge of pressure drop, liquid holdup, and often flow pattern (Flores *et al.*, 1999). Although an accurate prediction of oil-water flow in pipes is essential but it has not been explored as much as gas-liquid flow (Atmaca *et al.*, 2009). Formation water is produced along with the crude oil during a production stage and transported together to onshore through pipelines for further processing is considered as a typical phenomenon in oil and gas industry. Thus, an understanding of the behaviors of oil and water flow in pipelines is crucial specifically to many engineering applications which include the design and monitoring of the separation process, interpretation of production logs, and operation of flow lines and wells (Atmaca *et al.*, 2009). Apart from that, the knowledge of oil-water flow in pipes may contribute to the determination of the amount of free water in contact with the pipes' wall that could lead to corrosion or erosion problems (Trallero *et al.*, 1997). Regardless of their importance as aforementioned, liquid-liquid flows have not been studied as much as gas-liquid flow. Hence, the knowledge of the distinctive features of oil and water which encompasses the gas and liquid systems in pipes could be used in the future as a basis to understand the more complex case of gas-oil-water mixtures.

In some parts of the Malaysia oilfields are producing waxy crude oil, as shown in Appendix A. This phenomenon is due to the presence of paraffin hydrocarbon (C_{18} - C_{36}) and/or naphthenic hydrocarbon (C_{30} - C_{60}) in the crude oil (Mansoori, 1993), in other words, the presence of heavy components in the crude oil. When crude oil contains waxes, the properties of the oil will greatly change

especially the viscosity. The viscosity will differ depending on the compounds that present in the crude oil either light and intermediate hydrocarbons (i.e., paraffin, aromatic, naphthenic, etc.) or heavy organic (i.e., hydrocarbon compounds), such as asphaltenes, resin, mercaptans, or organo-metallics. There are numerous numerical and theoretical studies on the effects of viscosity in two phase flow systems, such as Russell *et al.* (1959), Arirachakaran *et al.* (1989), Angeli and Hewit (2000), Brauner (2002), Poesio *et al.*, (2008), and Vuong *et al.* (2009). Russell and co-workers have conducted an experimental study on the flow behaviour of oil-water in a horizontal pipe. They used oil with viscosity of 18.0 cp and different input of oil-water volume ratios as well as different superficial water velocities which resulted in the liquid holdup and flow pattern that were affected by viscosity and liquid input ratio. Oglesby (1979) investigated the oil-water flow in a pipe using three refined oil samples with different viscosity and varied the mixture velocities. It was found that pressure gradient and flow pattern were a function of mixture velocity, input water content, and oil viscosity.

In fact, there are numerous experimental studies on the significance of viscosity in the two phase flow such as from Russel *et al.* (1959), Arirachakaran *et al.* (1989), Oglesby (1979), Trallero (1995), Alkaya (2000), and Mckibben *et al.* (2000). Vuong *et al.* (2009) conducted an experimental study on high viscosity oil-water flow in horizontal and vertical pipes. During the experiment, the superficial velocities were varied as well as the inclination angle of the pipes and the pressure gradient, flow pattern and water holdup were recorded. The experimental result revealed that oil viscosities were found to have affected the pressure gradient, and at the same superficial water and oil velocities; the pressure increased with increase in oil viscosity. Therefore, a question arises in terms of the flow behavior in a pipeline when a waxy crude oil is introduced in the two phase flow system. This crude oil which contains waxes will definitely affect the flow behavior of a waxy crude oil-water two phase flow due to the viscosity changes, complex interfacial chemistry, and the formation of natural emulsion.

Kelechukwu and Yassin (2008) investigated the potential risk of paraffin wax related problems in Malaysian oilfields, namely Dulang, Penara, Bunga, Kekwa,

Angsi, and Tapis. They said that crude oil which contained waxes causes severe production problem due to the deposition of waxes in the pipes and ultimately lead to reduction of the internal diameter of the tubular, restricting or completely clogging the pipelines. These production losses contribute to the economic downturn of the petroleum industry. The complexity of two phase flow problems coupled with the presence of waxy crude oil has posed a colossal problem towards the petroleum industry when both are mixed together in a waxy crude oil-water two phase flow in pipes especially for the Malaysian oilfields that have a high potential risk of waxy problems. In reality, we need an accurate prediction of waxy crude oil multiphase flow behavior to transport and produce the waxy crude oil safely and economically. Since, there was no experimental studies done on the Malaysian waxy crude oil-water in a two phase flow system, thus it has restricted the deeper understanding of the complex flow behavior of waxy crude oil in pipelines. Therefore, an experimental study using the West Malaysia mild waxy crude oil in horizontal pipes through a 5.08 cm (2 in) ID pipe has been conducted to investigate the flow pattern, pressure drop, and water holdup in a two phase flow system.

1.2 Problem Statement

Dealing with an oil-water mixture in a pipeline leads to unique and complex problems in the oil and gas industry due to its complicated rheological behaviour, and vast difference in pressure gradient encountered for different flow patterns (Arirachakaran *et al.*, 1989). Although two phase flow of oil and water is normally occurred in pipes during production or transportation of petroleum fluids, but its hydrodynamic behavior under a wide range of flow conditions and inclination angles still creates a relevant unresolved issue of production optimization for the oil industry (Flores *et al.*, 1999). Moreover, emulsion of oil and water is another vital issue to be concerned in two phase flow system, where oil-water emulsions may show a Newtonian or non-Newtonian rheological behavior which directly associated to the pressure drop, flow pattern, and *in-situ* water volume fraction characteristic. Apart from that, if different oil properties or characteristics are being introduced into

the system, the hydrodynamic behavior of the systems will definitely change and therefore it cannot be simply applied to the existing two phase flow systems. Multiphase flows are characterized by the presence of various flow configurations and flow patterns. This can be identified by a typical geometrical arrangement of the phases in the pipes. Each of the flow patterns identified are the characteristics of flow mechanism, spatial distribution at the interface, and distinctive values for design parameters, such as liquid holdup and pressure drop (Flores *et al.*, 1999). There is distinct evidence that an accurate prediction and knowledge of oil-water flow patterns, flow rates and pipe inclination angles, and hydrodynamic parameters are crucial in many engineering applications especially in production systems. These include downhole metering, optimum string selection, production logging interpretation, production optimization, and artificial lift design and modelling (Flores *et al.*, 1999).

In fact, the major concern that many prominent researchers, such as Arirachakaran *et al.* (1989), Trallero *et al.* (1997), Flores *et al.* (1999), Nadler and Mewes (1997), Angeli and Hewitt (2000), Lovick and Angeli (2004a), overlooked was the accuracy of the experimental studies in a two phase flow system. Instead of using the actual crude oil, most of the models developed from experimental data were found to have used the artificial created-oil, such as refined oil and mineral oil. All these oils tested were subject to low-medium oil viscosity characteristics. Consequently, those models including the mechanistic models which were also developed based on the low-medium oil viscosity might under or over predict the oil-water flow behaviour (Sridhar *et al.*, 2011). It is noticeable that the properties and the behaviour of the artificial created-oil during experiments may pose separate issues in terms of similarities and differences with the actual crude oil in the two phase flow systems, hence the accuracy is very much uncertain. As discussed by Wang and Gong (2010) on the differences and similarities of the behaviour between mineral oil-water phases and the crude oil-water phases, they indicated that there were significant differences in terms of two phase flow characteristics when using mineral oil to the actual crude oil due to their differences in compositions. Since there are natural surfactants, such as asphaltenes and resin, present in the crude oil phase, oil and water may be easily formed. Generally, water-in-oil emulsion is quite stable, such that it contributes to a complex behavior of oil-water two phase flow system.

The flow behavior issues must be addressed seriously because an accurate prediction of pressure drop, water holdup, and flow pattern will contribute significantly to many engineering applications, namely in the petroleum and petrochemical industries.

1.3 Objectives

The objectives of this study were as follows:

- (1) To investigate the flow pattern, pressure drop, and water holdup of the West Malaysian mild waxy crude oil for a given set of flow rates in a closed flow loop system at the ambient condition.
- (2) To establish a flow pattern map for the West Malaysian mild waxy crude oil for the given flow conditions.

1.4 Research Scopes

In a two phase flow system, the major concern is closely related to the hydrodynamics behavior of the liquid-liquid flow in pipes. Generally, the hydrodynamic behavior is greatly influenced by two types of conditions, which are flow conditions and inclination angle. However, due to the equipment limitation, the study was conducted in a horizontal condition. The research study was focused mainly on the flow conditions of the typical Malaysian waxy crude oil-water in pipeline system. Below are the scopes of this study:

- (1) The waxy crude oil used in this research work was sourced from the Petronas' oilfields which are located offshore Peninsular Malaysia. It was collected from the Terengganu Crude Oil Terminal (TCOT), a Petronas' onshore terminal.

- (2) The filtered water used in this research was sourced from the Syarikat Air Johor (SAJ). The water was filtered to completely remove all the impurities, such as sand and rust, from the pipelines.
- (3) This research work focused on the flow pattern, pressure drop, and liquid holdup of waxy crude oil-water when they were flowing together in the pipeline system at an ambient condition. The scopes of flow pattern, pressure drop, and liquid holdup were described as follows:
 - (a) Flow patterns were determined by observing through a transparent pipe located in the test pipe section. The flow pattern was recorded using a video camera camcorder which was located at the transparent section. To discriminate the crude oil from water phase during an observation, a fluorescein powder was introduced into water to produce a luminous effect under an ultraviolet (UV) light.
 - (b) Pressure drop was determined using the pressure transducers which have been installed along the test section. The length for the pressure drop measurement was 3 m.
 - (c) Liquid holdup or *in-situ* volume fraction was determined by trapping the fluid flow using two quick closing valves. The trapped fluid was poured into a graduated container and left for three minutes depending on the types of holdup (as discussed in Chapter 4) before taking its volumetric measurement. This technique used the basic gravitational method to determine water and oil *in-situ* volume fraction or water holdup.
- (4) This research of waxy crude oil-water in pipes was conducted using a closed loop system. The closed loop was chosen instead of an open loop system because it could permit precisely the amount of oil and water to be used in the system and a stabilized flow rate could be achieved in a relative short time.
- (5) A flow pattern map would be established by taking into account the mixture velocities that produced different flow pattern under various flow conditions. A comparison was later made with the published flow pattern map.

- (6) Assumptions that have been made prior to conducting the research were:
- (a) No heat transfer between the outer pipe surface and the surrounding since the pipe had been totally insulated using a fiber cloth.
 - (b) The liquid-liquid flow in pipeline was immiscible.
- (7) The variable parameters for this study were:
- (a) Independent variables:
 - (i) The mixture velocities.
 - (ii) The ambient temperature (30°C).
 - (iii) The water cuts or input water fractions.
 - (b) Dependent variables:
 - (i) The pressure drop.
 - (ii) The *in-situ* water volume fraction or water holdup.
 - (iii) The flow patterns.

1.5 Significance of Study

Two phase flow or liquid-liquid flow is an unsolved problem until today especially for some flow issues which involving high viscosity oils and the crude oil which contains natural complex compounds. Many researchers such as Arirachakaran *et al.* (1989), Angeli and Hewit (2000), Brauner (2002), Abduvayt *et al.* (2004), and Zhang *et al.* (2010) were attempting to generalize the liquid-liquid system or the two phase flow system through the development of mechanistic models, but were facing high challenges due to the complexity of oil properties, flow conditions, different inclination angles and also flow patterns. A truly generalized

model of multiphase flow is almost impossible. Even though some of the multiphase flow models are reasonably accurate, but, due to the reasons aforementioned it could not be simply applied to the general flow model especially when encountered with high viscous oil or waxy crude oil.

Therefore, from this study, since the sample was the West Malaysia mild waxy crude oil, it was expected that we could predict and understand better the mild waxy crude oil-water behavior in a two phase flow system in order to economically and safely transport the waxy crude oil to onshore. Since the waxy crude oil-water two phase flow involved low density difference between oil and water and has been tested at ambient conditions, thus, the research findings can be adapted and applied in addressing the liquid-liquid two phase flow issues in petrochemical, food, or palm oil industries, apart from the oil and gas industry. A reliable flow pattern map for the West Malaysia mild waxy crude oil-water two phase flow developed through this research work could be applied in the industry development or as a platform to understand better the more complicated cases of gas-oil-water multiphase flow in the future.

1.6 Chapter Summary

This chapter briefly describes an oil-water two phase flow system, its definition and importance to the petroleum industry. It was complemented with the problems and difficulties encountered in a two phase flow system including the operational and designing part of offshore facilities and gaps between previous studies. The need to study the Malaysian waxy crude oils behaviour in a two phase flow system was also highlighted. To addressing these issues, the objectives and scopes of the research work were outlined. This chapter was complemented with the significance of this research work to the Malaysia's petroleum industry.

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