EXPERIMENTAL STUDY ON WAXY OIL–WATER HORIZONTAL FLOW AT TEMPERATURES ABOVE THE WAX APPEARANCE TEMPERATURE

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Petroleum Engineering)

Faculty of Chemical and Energy Engineering
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MAY 2017

This thesis is dedicated to my beloved wife and parents, in recognition of their continual love, encouragement, and support.

ACKNOWLEDGEMENT

In the name of Allah, the most Compassionate, the most Merciful

In preparing this thesis, I was in contact with many people, researchers, and academicians. Here, I wish to express my deepest appreciation and gratitude in my acknowledgments to all who have contributed and guided me through. In particular, I would like to record my sincere gratitude to my main research supervisor, Associate Professor Dr. Muhammad bin A. Manan, for his patience, encouragement, guidance, and especially for his confidence in me. I am also very thankful to my co-supervisors, Associate Professor Issham bin Ismail, and Professor Eng. Dr. Rahmat bin Mohsin, for their precious advices, endless support, and assistance. I feel very fortunate and honoured to have worked especially with Associate Professor Issham bin Ismail who benefited me with his great wisdom, invaluable experiences and knowledge in academic and non-academic life. My growth as a researcher was enriched and inspired by his passion and genius ideas in science and design.

I am also very grateful for the financial support and the opportunity given by the Ministry of Higher Education of Malaysia and Universiti Teknologi Malaysia under the Fundamental Research Grant Scheme (Vot no: 4F136) and Research University Grant Scheme (Vot no: 01H68), respectively. My special thanks also to Petronas for supplying the crude oil, UNIPEM for testing and characterizing the research samples, MD Interactive Enterprise for the rig construction and fabrication, Suria Pembekal Umum Sdn. Bhd. and Grief Malaysia Sdn. Bhd. for their assistance in supplying chemicals and relevant materials to make this project a success.

Aside that, I would like to express my deepest gratitude to Mr. Mior Zaiga and Mr. Rohaizad, Staff Process Engineers of Petronas Carigali Sdn. Bhd. for their regular industrial discussions on the research project. Their industrial experience

truly furnished a valuable source of information and insight on the research application towards the oil and gas industry. Special thanks are also conveyed to Mr. Zaid and Mr. Samsol of UTM-MPRC Institute for Oil and Gas, Mr. Redhuan Ramlee, the Head Technician of the Gas System Laboratory, Mr. Ahmad Norani Sadiron, the Head of the Central Store, and FPREE's academic and technical staff for their guidance, assistance, and support.

Finally on my personal note, I would like to express my heartfelt appreciation to my dearly beloved wife, Shaghayegh Mohammadi, without whom I would not have the strength and perseverance in pursuing this study. Most importantly to my beloved parents, Hamid Piroozian and Mina Dashti, for their prayers and words of wisdom that always enlighten me and help me gaining my spiritual right on track. Last but not least to my research team members, Mr. Mahmmoud Hemati and Mr. Ahmad Shamsul Izwan Ismail, for the fruitful and thoughtful discussion throughout the research studies, and not to forget, in helping me to accomplish the experimental works. Their views and tips were truly useful and are appreciated. Without their continued support and interest, this thesis would not have been the same as presented here.

ABSTRACT

Temperature sensitivity of waxy crude oils makes it difficult to study their flow behaviour in the presence of water especially near their wax appearance temperature (WAT). In this study, a method was proposed and implemented to mitigate such difficulties by predicting mixture temperatures prior to experimental flow of a typical Malaysian waxy crude oil and water in a designed horizontal multiphase flow loop. To observe this method in action, mixture temperatures, pressure drops and liquid holdups were experimentally measured for mixture velocity ranging from 0.2 to 1.7 m/s in a carbon steel horizontal pipe at three different temperatures slightly above the WAT. Several correlations were also applied to predict the pressure gradients and their results were compared with the experimental values. Accordingly, flow patterns were determined by considering a combination of visual observations, pressure drop interpretations and free water measurements. Moreover, the effect of emulsified water droplets on accelerating the wax crystallization process above the WAT under dynamic and static conditions was examined in connection with the results of the two-phase flow experiments. The results showed the success of the proposed method in predicting the mixture temperature with an accuracy of ±0.5 °C. The results of pressure drop revealed a dependency on mixture velocity, input water fraction, flow pattern and the parameters that flow pattern is a function of (such as pipe wettability, superficial velocities, and oil composition). In dual continuous flows, the performance of two-fluid model was comparatively better than homogenous model with average deviation of 17.9 and 26.7%, respectively. Despite operating the experiments above the WAT, the deposition of wax crystals on the pipe wall was evidenced for some of the flow patterns which, by implication, authenticates the influence of emulsified water on elevating the WAT in dynamic flow conditions. Classification of the flow patterns based on the wax deposition yielded an original flow pattern map composed of nine patterns among which new configurations were evidenced for annular flows. In addition, all the flow patterns were affected by the entrance effect and a layer of water-in-oil emulsion was observed for all the flow conditions. From the experiments under the static conditions, a sharp increase in the WAT was found with the presence of water in the system, regardless of the volume of water. Greater deviations became apparent at higher water volume fractions and rotational speeds, which resulted in the formation of a larger number of droplets. The results of this study provide a progressive introduction to help flow assurance engineers to understand the process of wax crystallization and deposition under two-phase flow conditions in horizontal pipelines, and to ultimately develop more effective wax management strategies.

ABSTRAK

Kesensitifan minyak mentah berlilin terhadap perubahan suhu menyukarkan kajian tingkah laku alirannya dengan kehadiran air terutama pada suhu yang berhampiran dengan suhu penjelmaan lilinnya (WAT). Dalam kajian ini, satu kaedah telah dicadang dan dilaksana bagi mengurangkan permasalahan terbabit iaitu dengan meramal suhu campuran sebelum bermulanya kajian aliran minyak mentah berlilin Malaysia dan air, di dalam gelung mendatar aliran berbilang fasa. Bagi mencerap keadaan uji kaji dinamik ini, suhu campuran, kejatuhan tekanan, dan cecair tertahan telah diukur untuk halaju campuran yang berjulat dari 0.2 m/s hingga ke 1.7 m/s di dalam paip keluli karbon mendatar pada tiga suhu berlainan yang berada sedikit di atas WAT. Beberapa sekaitan turut digunakan untuk meramal kecerunan tekanan dengan hasilnya dibandingkan dengan nilai-nilai uji kaji. Dengan itu, corak aliran ditentukan dengan mempertimbang gabungan pemerhatian visual, kejatuhan tekanan, dan air bebas yang diukur. Selain itu, kesan titisan air beremulsi terhadap peningkatan proses penghabluran lilin di atas WAT pada keadaan dinamik dan statik turut dikaji dengan mengaitkan hasil uji kaji aliran dua fasa. Hasil kajian menunjukkan kejayaan kaedah yang dicadang dalam peramalan suhu campuran dengan ketepatan ±0.5 °C. Keputusan uji kaji tentang kejatuhan tekanan mendedahkan kebergantungannya terhadap halaju campuran, pecahan air masukan, corak aliran dan parameter lain yang mempengaruhi corak lain (misalnya kebolehbasahan paip, halaju permukaan, dan komposisi minyak). Dalam aliran berterusan duaan, prestasi model dua bendalir adalah lebih baik berbanding model homogen dengan masing-masing sisihan purata ialah 17.9 dan 26.7%. Walaupun uji kaji dilaksanakan di atas WAT, pemendapan hablur lilin pada dinding dalaman paip didapati masih berlaku dalam beberapa corak aliran, yang mengesahkan kesan air beremulsi terhadap peningkatan WAT pada keadaan aliran dinamik. Pengelasan corak aliran berdasarkan pemendapan lilin telah menghasilkan peta asli corak aliran yang mencakupi sembilan corak aliran termasuk penemuan baharu untuk aliran anulus. Semua corak aliran dipengaruhi kesan masukan dan lapisan emulsi air-dalam-minyak yang diperhatikan untuk semua keadaan aliran. Berdasarkan uji kaji pada keadaan statik, peningkatan mendadak WAT didapati berlaku dengan kehadiran air di dalam sistem, tanpa bergantung kepada isi padu air terbabit. Pelencongan lebih besar didapati berlaku pada pecahan isi padu air dan laju putaran yang lebih tinggi sehingga terbentuknya titisan air yang lebih banyak. Hasil kajian ini mampu membantu jurutera jaminan aliran bagi memahami proses penghabluran lilin dan pemendapannya pada keadaan aliran dua fasa di dalam talian paip mendatar, dan seterusnya berupaya untuk membangunkan strategi pengurusan lilin yang lebih berkesan.

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C - carbon

IFT - interfacial tension

L_e - entrance length

d - pipe diameter

ID - inner diameter

F_i - inertia force

v - volume of a single oil droplet submerged in a water medium

g - gravitational acceleration

m_o - oil droplet mass

a - acceleration of droplet

H_o - oil holdup

H_w - water holdup

V_o - volume of oil

V_w - volume of water

V_t - total volume of oil and water in pipe

$\left(\frac{dp}{dl}\right)$ - pressure gradient

dp - pressure drop

dl length of pressure drop

f - Darcy-Weisbach friction factor

D - pipe inner diameter/hydraulic diameter

Re - Reynolds number

C, n - Blasius constants

A, B - Chirchill constants

R_g - fraction of tube filled with gas

R_l - fraction of tube filled with liquid

$\dot{M}$ - mass flow rate

n - Theissing interaction parameter

A - cross-sectional area

A_O , A_W - area occupied by oil, water

S - contact periphery

S_i - interfacial length

S_O - oil-wetted wall perimeter

S_W - water-wetted wall perimeter

h_W - water height

B - Bond number

r_c - curvature radius

f_k - wall friction factor of the faster phase

C_i - correction factor

C_s - empirical factor

f_{cor} - corrected friction factor

k - Ball and Richmond model corresponds to the geometry of the dispersed droplets

k - kilo

H_2S - hydrogen sulfide

CO_2 - carbon dioxide

N_2 - nitrogen

Q - quantity of the transferred energy as heat

m - mass

c, c_P - specific heat capacity

T - temperature

T^0 - any arbitrary reference temperature

SG - specific gravity

ΔG - change in Gibbs free energy

ΔH - change in enthalpy

ΔS - change in entropy

$E_{R,i}$ - relative error in percent for component i

E_{AR} - absolute relative error

E_1 - average relative error

E_2 - standard deviation of average relative error

E_3 - absolute average relative error

E_4 - standard deviation of absolute relative error

H_{ew} - emulsified water holdup

t - time

mg - milligram

µL - microliter

N - Newton

W - Watt

mW - milliwatt

mA - milliampere

in - inch

HP - horsepower

L - liter

RPM - revolutions per minute

g - gram

J - Joule

K - Kelvin

hr - hour

hrs - hours

min - minute

ml - milliliter

m - meter

mm - millimeter

Sec, s - second

Pa - pascal

mPa - millipascal

% - percent

vol. % - volume percent

wt. % - weight percent

° - degree

^{o}C - degree Celsius

kcal - kilocalorie

UOP - characterization factor

Greek letters

ρ - fluid density

μ - fluid viscosity

β - pipe inclination angle

ϑ - fluid velocity

ϑ_o - *in-situ* (actual) oil velocity

ϑ_w - *in-situ* (actual) water velocity

ϑ_{so} - oil superficial velocity

ϑ_{sw} - water superficial velocity

λ - input volume fraction

$\lambda_{o,\ \mathrm{critical}}$ - critical oil volume fraction at which inversion occurs

ε - pipe roughness

X , Φ - Lockhart-Martinelli parameters

τ - shear stress

π - pi

Δ - change

σ - interfacial tension

θ - contact angle

φ_0 - interface view angle at the center of the pipe

φ^* - interfacial angle

γ - proportionality factor

α - wave amplitude

Subscripts

i - inertia; oil–water interface; initial

o - oil

w - water

m - mixture

s - superficial

t - total

f - frictional; final

ele - elevational

acc - accelerational

g - gas

l - liquid

TP - two-phase

d - dispersed phase

c - continuous phase; calefactory phase

e - endothermic

1 - lighter phase; model 1

2 - heavier phase; model 2

cor - corrected

act - actual

prd - predetermined

exp - experimental

LIST OF ABBREVIATIONS

AMTEC	-	Advance Membrane Technology Research Centre
API	-	American Petroleum Institute
ASTM	-	American Society for Testing and Materials
ISO	-	International Organization for Standardization
MPRC	-	Malaysia Petroleum Resources Corporation
PETRONAS	-	Petrolium Nasional Berhad
TCOT	-	Terengganu Crude Oil Terminal
UNIPEM	-	Unit Perkhidmatan Makmal
UTM	-	Universiti Teknologi Malaysia
GC–MS	-	gas chromatography–mass spectrometry
DSC	-	differential scanning calorimetry
NI	-	national instrument
WAT	-	wax appearance temperature
PP	-	pour point
w/o	-	water-in-oil
o/w	-	oil-in-water
SS	-	stratified smooth
SW	-	stratified waxy
SM	-	stratified mixed
DC	-	dual continuous
Dw/o&o	-	dispersion of water in oil and oil layer
Do/w&w	-	dispersion of oil in water and water layer
FD	-	fully dispersed
IDw/o	-	inhomogeneous dispersion of water in oil
IDo/w	-	inhomogeneous dispersion of oil in water
HDw/o	-	homogeneous dispersion of water in oil
HDo/w	-	homogeneous dispersion of oil in water

PCAF	-	perfect core-annular flow
ST-PE	-	stratified flow with partial emulsion of water in oil at interface
SW-PE	-	stratified wavy flow with partial emulsion of water in oil at interface
WDC	-	wax deposit and dual continuous flow
WEA-PE	-	wax deposit and eccentric annular flow with partial emulsion of water in oil at interface
WEA-E	-	wax deposit and eccentric annular flow with full emulsion of water in oil
WEA-DC	-	wax deposit and eccentric annular flow of dual continuous
WFDo/w-TLo	-	wax deposit and fine dispersion of oil in water with thin layer of oil at the top of the pipe
WFDo/w-So	-	wax deposit and fine dispersion of oil in water with streaks of oil at the pipe wall
SR	-	slip ratio
TFM	-	two-fluid model
UV	-	ultra-violet
CNT	-	classical nucleation theory
AARE	-	average absolute relative error
MDS	-	mean droplet size
ASA	-	accessible surface area
WVF	-	water volume fraction
MDS	-	mean droplet size
OES	-	overestimated
UES	-	underestimated
QCV	-	quick closing valve
n-alkanes	-	normal alkanes

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CHAPTER 1

INTRODUCTION

1.1 Research Background

The expanded territory of petroleum production has given rise to the advent of a new field in petroleum industry termed flow assurance. By definition, flow assurance comprises all activities that guarantee the continuous stable hydrocarbon production with minimum costs and environmental hazards from a reservoir to the target market at any environmental conditions and within the whole reservoir's productive life (Bai and Bai, 2005). In this regard, flow assurance engineers must overcome such challenges, firstly by anticipating the potential difficulties that may arise at different stages of production, and secondly by proposing the most effective production plan prior to operation (Aske and Statoil, 2011). In doing so, reviewing the production fluid(s) and operational conditions at different production stages is always on the list of priorities.

At early stages of production from an oil well, the main produced reservoir fluid is the crude oil which is usually regarded as a single oil phase despite the presence of usually insignificant amount of formation water in the producing oil. As time goes by and the reservoir pressure declines due to the depletion of the oil zone, the underlying aquifer water will gradually enter the wellbore as a response to the induced pressure gradient between the surrounding water and the wellbore. Accordingly, the amount of the existing water in the production line is augmented synchronously with the age of the well. Thus, mature oil fields experience high water cut in the period of their productive life. However, in some cases, an oil well might be still economical to operate even for water cut as high as 90% which is highly dependent on the oil price and geographic location of the well (Jepson *et al.*, 1996; Elseth, 2001; Kumara *et al.*, 2009). If the perforation interval is close to the gas/oil interface gas might eventually be produced.

Owing to the nature of formation water and its accompanied components (i.e., salt and sediments), severe obstacles may arise and affect the profitability of production. Corrosion, paraffinic wax deposition, reduction of oil flow area in pipe, emulsions and hydrates formation are some examples of flow assurance problems caused by the presence of water. Therefore, it is more preferable to transport dehydrated oil and gas through single phase pipe flow wherever possible to avoid such hardships. However, the gradual growth in oil demand has reached a point where production from deepwater oilfields is the only key remained for such a huge request (Khain and Polyakova, 2004). Fortunately, progressive achievements in offshore oil exploration and drilling technology have recently made it feasible to explore and develop new remote deepwater oil reservoirs, which had been once unobtainable. The transportation of the extracted crude oils from such reserves often takes place through long-distance (sometimes over 200 km) subsea multiphase pipelines to reach various destinations (Elseth, 2001). This vast distance makes it unprofitable to have distinct pipelines for each phase (i.e., oil, water, and gas). The alternative is to transport the fluids through one single pipe (three-phase flow) or at least two pipelines (one for gas and the other for liquids). Thus, attempts are needed to investigate multiphase flow behaviour under diverse flow conditions to identify influential parameters for controlling possible problems during transportation.

A survey on the studies performed on three-phase flow indicates that in most cases oil and water are considered as a single liquid phase to simplify the study in the form of gas–liquid flow (Wyckoff and Botset, 1936; Taitel *et al.*, 1995; Chen and Guo, 1999; Spedding *et al.*, 2005; Wang *et al.*, 2010; Gao and Jin, 2011; Xu *et al.*, 2012). This is mostly due to the relative similarity between the oil and water densities and a distinguishable dissimilarity between the densities of the liquids and gas. However, the results of recent studies on liquid–liquid flow have shown that the flow characteristics of two immiscible fluids can be very different from the flow characteristics of each individual liquid in many respects (Brauner, 2003; Chakrabarti *et al.*, 2005; Zhao *et al.*, 2006; Cai *et al.*, 2012; Du *et al.*, 2012; Gao *et al.*, 2013; An *et al.*, 2014; Bertola, 2014; Ismail *et al.*, 2015). This highlights the importance of studying different aspects of oil–water two-phase flow to recognize and understand the potential impediments during the flow which are essential for having effective production plans.

The liquid–liquid flow encompasses wide areas of the petroleum industry, starting from the oil reservoir production to the refinery units. In this regard, pressure drop, liquid holdup, and flow pattern have been studied as the major flow characteristics under different flow conditions (Trallero *et al.*, 1997; Angeli and Hewitt, 2000; Lovick and Angeli, 2004; Rodriguez and Oliemans, 2006; Xu, 2007; Vielma *et al.*, 2008; Cai *et al.*, 2012; Hanafizadeh *et al.*, 2015). Several correlations for pressure gradient prediction have been also proposed based on the experimental results which are in most cases incompatible for diverse fluids characteristics (Chakrabarti *et al.*, 2005; Grassi *et al.*, 2008; Al-Wahaibi, 2012; Edomwonyi-Otu and Angeli, 2015). Substantial variations can, furthermore, be found in the published results for holdups and flow patterns depending on the methodology applied. However, despite all the existing discrepancies between the findings in this research area, there exists a general agreement that shows the pressure drop dependency on the flow pattern and mixture velocities. This implies the significance of fluids configuration in pipes in every study of multiphase flow.

1.2 Statement of Problem

The presence of paraffinic waxes, regardless of their proportion, in all types of crude oils highlights the significance of two-phase flow study with respect to these components (Manning and Thompson, 1995). Nevertheless, research works done on oil–water two-phase flows have mostly been restricted to the use of model oils (i.e., synthetic or mineral oils) rather than crude oils (Cai *et al.*, 2012; Kee *et al.*, 2014; Tan *et al.*, 2015). Although this practice is accepted as an attempt to improve the general knowledge on the subject, actual oilfield cases may not be covered. In recent years, successful efforts have been made using viscous model oils and/or crude oils to provide data which are considered to be more representative of oilfield production conditions. The important works of Fairuzov *et al.* (2000), Vuong *et al.* (2009), Xiong *et al.* (2011), Zhang *et al.* (2012), Yusuf *et al.* (2012) and Jing *et al.* (2016) are just a few to be mentioned. Experimental data obtained from these works have sometimes shown new insights and revealed previously undetected phenomena or supported a new phenomenon as compared to those working on the model oils. Fairuzov *et al.* (2000), for instance, performed a research on the flow pattern transitions via employing sampling probes for mixture flows of a light crude oil and water in a horizontal pipeline. They observed that even in stratified flows small portions of dispersed water droplets remained within the crude oil. Kokal (2005) demonstrated the formation of relatively stable water-in-oil emulsions due to the presence of natural emulsifiers and heavy components such as asphaltenes, resins, organic acids, and waxes among the crude oil components. Later on, Xiong *et al.* (2011) reported that at water fractions above 50% there was a considerable difference between the obtained flow patterns from heavy crude oil with that of model oils with similar viscosities. Moreover, they stated that unlike the model oils, w/o emulsions persistently existed in all cases and this was ascribed to the crude oil natural emulsifiers. While, the occurrence of this phenomenon has never been evidenced for the cases where the model oils have been utilized. This implies that, an overly simplistic model oil cannot be a perfect representative of complex crude oils in terms of flow behavior.

In order to determine the effect of wax particles on the behavior of two-phase flow, the characteristics of flow should be investigated at temperatures close to the WAT. This encompasses a range of temperatures at which crude oil retains its flowability and is transported in actual operational conditions. Therefore, controlling the mixture temperature especially in waxy crude oils and water integration in two-phase flow system is crucial. This is fundamental to avoid any uncontrolled abrupt changes in temperature which can trigger undesirable effects on operational conditions. Despite the fact that great effort has been devoted to the study of oil–water two-phase flows, few studies have paid heed to the role of temperature. As for the influence of temperature, available literatures on oil–water two-phase flow are divided into two major groups. Firstly, those studies in which the role of temperature has been completely ignored, such as research works carried out by Xu *et al.* (2010), Dunia *et al.* (2011), Zhang *et al.* (2011), Al-Wahaibi (2012), Cai *et al.* (2012), Tan *et al.* (2013), Zhai *et al.* (2014), Edomwonyi-Otu and Angeli (2015), and Ismail *et al.* (2015). The second group comprises those studies taking the effect of temperature into account in the absence of wax components (Xiong *et al.*, 2011; Lü *et al.*, 2012; Filippov *et al.*, 2014). This could be due to the use of synthetic or treated oil samples without the presence of paraffin wax in their systems, similar to the works of Lü *et al.* (2012) and Filippov *et al.* (2014). Even though wax may be found as a constituent of the oil sample in some previous research works, Xiong *et al.* (2011) as an example, the operational temperatures were set much higher than the WAT. Therefore, a key limitation of prior studies is that they did not address the temperature conditions at which problems associated with waxy crude oils may occur in oil–water two-phase flow systems.

It should be noted that the studies on paraffin deposition under two-phase flow conditions are mostly conducted using a flow loop apparatus equipped with a pipe-in-pipe heat exchanger (Sarica and Panacharoensawad, 2012). The aim is to simulate the deposition process in subsea transportation pipelines by creating a temperature gradient between flowing fluids and pipe walls. For such a purpose, the inner pipe wall temperature is kept below the WAT of the dehydrated crude oil. The main drawback of this technique for research purposes is that the formation of the wax crystals (at the wall and in the bulk) is only attributed to the induced radial temperature gradient caused by decreased temperature of the pipe wall. Therefore, any possible thermal change in the crude oil due to the presence of emulsified water is neglected. In these studies, the WATs of the dehydrated oils are measured and assumed to be representative of the entire system (i.e., mixture of oil and water). Based on these assumptions, the presence of wax crystals in the designed systems is expected only at temperatures below the WAT of the dehydrated crude oils, which may not represent the real case in the oilfield. The measurements and results in these situations may lead to substantial errors. The studies pertaining to waxy crude oils, however, have revealed that the WAT is influenced by several parameters, including kinetics, the oil (solvent) and wax composition, polydispersity, pressure, cooling rate, and the presence of impurities (Adhvaryu *et al.*, 2002; Alcazar-Vara and Buenrostro-Gonzalez, 2013). Therefore, any type of impurity existing in a hydrocarbon system causes variations in the value of the WAT. This phenomenon can also be extended to the field study of oil/water two-phase flow systems wherein waxy crudes are selected as the oil phase and w/o emulsion is a part of the flow, especially at temperatures near the WAT. Li and Gong (2010) are among the few researchers who have acknowledged the effect of water cut on the WAT. According to their results, the change in WAT for different water cuts did not exceed 0.15 °C, which indicates that the effect of water cut on the WAT is insignificant. Nevertheless, the research results did not provide adequate rationale for these investigators to put forth conclusions based on their findings; therefore, they merely reported the results.

1.3 Objectives

This study was primarily based on the following objectives:

(1) To propose and implement a successful method to predict mixture temperatures of a crude oil and water flowing in a horizontal pipe for preset flow conditions prior to the experimental tests.

(2) To experimentally investigate the flow patterns of waxy crude oil–water two-phase flows in a designed horizontal multiphase flow loop at mixture temperatures slightly above the crude oil initial WAT and subsequently to establish a new flow-pattern map.

(3) To examine the effect of flow pattern, temperature, water cut, and mixture velocity on pressure drop in order to find the dominant parameter at different flow conditions.

The initial specific aim of this research work was to extend the study of oil–water two-phase flow from non-waxy to waxy crude oils in the hope that the findings can open a window towards the understanding of waxy crude oils flow behavior in two-phase flow systems. Therefore, as a first attempt to study a type of waxy crude oil in an oil–water two-phase flow system, the experiments were conducted at temperatures slightly above the WAT of the crude oil to avoid the complexity of wax precipitation. Nevertheless, it was soon evident that the wax precipitation was inevitable at the presence of water under such operating temperatures during the two-phase flow. This phenomenon suggested additional objective to this study as follow:

(4) To scrutinize the effect of the presence of water, i.e., the water volume fraction (WVF) and the mean droplet size (MDS), on the WAT of water-in-waxy-crude-oil emulsions.

1.4 Scope

To accomplish this study, I have designed, constructed, and commissioned a flow test facility at the Malaysia Petroleum Resources Corporation Institute for Oil and Gas (UTM-MPRC Institute for Oil and Gas), Universiti Teknologi Malaysia (UTM), Johor Bahru. The facility is capable of experimentally simulating single- or two-phase flows of oil and water in a horizontal pipe section. However, this study focused on the concurrent flow of water and a typical Malaysian waxy crude oil at three mixture temperatures (i.e., 26, 28, and 30 °C) under various flow conditions. To fulfill the aforementioned objectives, I have widened the scope of my investigation into the followings:

(1) Thermal treatment of the crude oil, first, to redissolve potential wax crystals within the crude; second, to reduce the water content to a minimum of 0.05% of the total volume; and third, to evaporate the existing light ends in the crude oil. The treatment involved simultaneous heating and manual stirring of the crude oil at 80 – 85 °C in a specific thermal treatment system for about two hours.

(2) Rheological characteristics measurements of the oil and water samples at different temperatures.

(3) Identification of the crude oil compositions using gas chromatography–mass spectrometry (GC–MS) to recognize the potential natural surfactant components within the oil.

(4) Evaluation of the predictive accuracy of the two proposed models against the experimental results for the mixture temperatures obtained during the attempt to reach and maintain the mixture temperature as close as possible to the one of the three mixture temperatures of 26, 28, and 30 °C for oil and water superficial velocities ranging from 0.1 m/s to 0.7 m/s and 0.1 m/s to 1.0 m/s, respectively.

(5) Analogy between the new obtained flow pattern maps from the crude oil of this study with the existing maps found in open literature for further analysis.

(6) Employing the available pressure gradient models, namely two-fluid model (for both curved and planar interfaces) and homogenous model, to predict the pressure gradient; and comparing the results with the experimental data to

determine the most compatible model based on the observed flow patterns in this study.

(7) Preparation of water-in-oil emulsion samples of different water-cuts (10 to 70%) under three distinct rotational speeds (600, 900, and 1200 RPM).

(8) Conducting a thermal analysis using differential scanning calorimetry (DSC) to elucidate the mechanism influencing the WATs of the emulsion samples by considering the Gibbs free energy concept.

1.5 Significance of Study

This study is an attempt to enlarge the knowledge on concurrent transportation of oil and water through a single horizontal pipeline while the oil phase is a type of waxy crude oil. To the best of our knowledge, there is no experimental work in this field accomplished using any typical Malaysian waxy crude oil despite the fact that there are numerous mature Malaysian oilfields producing waxy crude oils through two-fluid phase flow systems. Therefore, it is believed that this is the first group of researchers who are working in this area by utilizing a domestic crude oil sample. Thus, the experimental results can be used as a basic source for industrial purposes so that the design of pipeline systems can be effectively established to handle waxy crude oil transportation. In most cases, pipelines are a cost effective method of transportation when compared to other alternates such as barge or tanker shipment.

The present study also proposes a new technique which opens up new doors for experimental investigations on the flow behaviour of waxy crude oils at temperatures close to the WAT. With the use of this approach not only mixture temperature is controlled but also it prevents the formation of unwanted wax crystals due to the fast cooling rate at the system’s inlet. Therefore, this novel method can be applied as a practical solution to study the flow behaviour of waxy crude oils in oil/water two-phase flow systems at temperatures relatively close to the WAT.

In this study, I also extend my attention to the role of water, as an impurity within the crude oil, on the WAT of water-in-oil emulsions. If the possible thermal effects of the presence of water on the emulsion WAT are neglected, the consequence can be the unwanted deposition of wax crystals at temperatures greater than the WAT of the crude oil. This may threaten the success of flow assurance operations, especially in temperature-sensitive systems, such as the offshore pipeline transportation of waxy crude oils. The results of this part of the study may provide reference and insights for further study of w/o emulsions closer to the actual oilfield conditions whereby a reliable correlation can be developed for prediction of the WATs of w/o emulsions by identifying the WATs of dehydrated crude oils.

In general, the results of this study provide a progressive introduction to help flow assurance engineers to understand the process of wax crystallization and deposition under multiphase flow conditions in horizontal pipelines, and to ultimately develop more effective wax management strategies.

1.6 Thesis Structure

The thesis is structured to comprise five main chapters with subsections. Chapter 1 covers the research background, statements of the problems, research objectives and scopes, and significance of study.

Chapter 2 gives descriptions of previous research works associated with liquid–liquid two-phase flows in horizontal pipelines and reports the results obtained. A brief reference is also made to some of the models suggested to predict the pressure gradient of two-phase horizontal flows. The section also discusses some fundamental aspects of waxy crude oils and explains some of the important terms used in this study.

Chapter 3 gives a detailed description of the pilot-scale facility and the instrumentation used in the experimental work. The methods used for data processing and analysis are also described. Besides, two analytical models for predicting mixture temperatures are derived and the procedure to reach the desired mixture temperatures during the course of the experiments is addressed. Furthermore, the materials and measurements regarding the study of the effect of emulsified water on the WATs of water-in-waxy-crude-oil emulsions are thoroughly presented.

Chapters 4, first, presents the mixture temperature results obtained from both experimental and the two models. Later, it presents the findings on the flow patterns, pressure gradient, and holdup. Comparisons of the experimental results with the models and available literature data can be also found in this chapter. Eventually, this chapter describes the thermodynamic effect of the emulsified water on the WAT of the emulsion which is highly probable to be formed during the concurrent transportation of water and waxy crude oil in a horizontal pipe based on the results of this study.

Finally, Chapter 5 summarizes the conclusions of this work and proposes recommendations for future work.

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