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NON-NEWTONIAN VISCOSITY BEHAVIOR INVESTIGATION FOR MALAYSIAN WAXY CRUDE OILS AND IMPACT TO WAX DEPOSITION MODELLING

ASTRIYANA ANUAR[1,2*], ISMAIL MOHD SAAID[2], PETRUS TRI BHASKORO[3] AND ROHAIZAD MOHD NORPIAH [2]

[1]*Department of Petroleum Engineering, Universiti Teknologi PETRONAS, Perak, Malaysia*
[2]*Project Delivery and Technology, PETRONAS, Kuala Lumpur, Malaysia*
[3]*Department of Advanced Material and Subsea Technology, PETRONAS Research Sdn. Bhd., Selangor, Malaysia*

[*]*Corresponding author: astriyana_21000006@utp.edu.my*

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ABSTRACT: Wax deposition is one of the major risks that causes a serious threat to pipeline transportation during operation, if not prevented. The remediation actions are usually costly; hence mitigation methods are in place to completely avoid the issues from happening. The wax deposition modelling technique has been accepted as a tool to design and continuously optimize the wax management strategy. Non-Newtonian oil-wax viscosity is an important parameter affecting wax deposition in pipelines. The present and widely used viscosity model assumes exponential behavior as observed in the emulsion system. In this paper, it is demonstrated that this assumption may not be suitable for Malaysian waxy crude oil applications due to instantaneous change of viscosity below WAT and PPT. This paper focuses on the application of the Pedersen and Ronningsen viscosity model available in the commercial fluid and flow simulators namely PVTsim ®, Multiflash ® and OLGA ® which are widely used by the flow assurance fraternities, and how it will impact wax deposition prediction accuracy specifically when applied to Malaysian waxy crude oils.

ABSTRAK: Pemendapan lilin adalah salah satu risiko utama yang menyebabkan ancaman serius kepada pengangkutan saluran paip semasa operasi jika tidak dicegah. Proses membaiki biasanya memerlukan kos yang tinggi; oleh itu kaedah mitigasi disediakan bagi mengelakkan isu ini daripada berlaku. Teknik model pemendapan lilin telah diterima sebagai alat bagi mereka bentuk dan merupakan strategi optimum pengurusan lilin secara berterusan. Kelikatan minyak-lilin bukan Newton adalah salah satu parameter penting yang mempengaruhi pemendapan lilin dalam saluran paip. Anggaran model kelikatan semasa yang digunakan secara meluas menjangkakan tingkah laku eksponen seperti yang diperhatikan dalam sistem emulsi. Kajian ini menunjukkan bahawa kaedah anggaran mungkin tidak sesuai bagi aplikasi minyak mentah berlilin Malaysia disebabkan oleh perubahan kelikatan serta-merta di bawah WAT dan PPT. Kertas kerja ini memberi tumpuan kepada aplikasi model kelikatan Pedersen dan Ronningsen yang terdapat dalam cecair komersial dan simulator aliran iaitu PVTsim ®, Multiflash ® dan OLGA ® yang digunakan secara meluas oleh persatuan jaminan aliran, dan keberkesanan pada ketepatan anggaran pemendapan lilin khususnya apabila digunakan pada minyak mentah berlilin Malaysia.

KEYWORDS: *waxy crude oil; viscosity; non-Newtonian viscosity; wax deposition; flow modelling; rheology*

1. INTRODUCTION

Flow assurance (FA) brings the most significant financial impact especially for deepwater development and FA-critical fields (i.e., fields with severe FA issues). The risks and potential issues need to be defined as early as possible prior to development, and the types of flow assurance issues and their management plans are usually included in the field's overall operating philosophy to ensure safe and unrestricted transportation of hydrocarbon from reservoir to customer. Wax deposition is one of the major risks that causes a serious threat to pipeline transportation during operation, if not prevented. When the surrounding temperature drops below Wax Appearance Temperature (WAT), wax crystallization happens followed by deposition of the precipitated wax solids with increasing thermal gradient (due to low surrounding seabed temperature). Wax deposition of crude oil in pipelines reduces the flow area with time which affects the crude production and transportation. Wax deposits are usually removed mechanically using a scraper pig and is done periodically as the wax builds up in the pipeline. Additionally, to mitigate wax deposition in the pipelines, chemicals such as wax inhibitors, dispersants or wax crystal modifiers are commonly used in industry [1].

For a new field development, a reservoir fluid sampling and analysis program is executed as part of lab characterization activities to quantitatively evaluate the wax's properties and its tendency to deposit. Flow assurance engineers use this information as input into the fluid and flow software and heavily rely on the results of these modelling activities in defining the wax management strategy philosophy that should cover the entire field life cycle. Additionally, during the production stage, wax deposition modelling has been accepted as a tool to effectively optimize the pipeline operating envelope, specifically in determining pigging frequencies and reviewing chemical injection effectiveness in inhibiting wax deposition, however, several published papers have reported on the over and under-estimation of wax deposition rates. Consequently, modelling techniques have been observed to be unreliable without representative input and further model benchmarking or validation with experimental or field data [2,3]. Non-Newtonian oil-wax viscosity is identified as an important parameter affecting wax deposition in the pipeline [2].

This paper investigates the non-Newtonian behaviors of Malaysian waxy crude oils and reviews the suitability of the present wax viscosity model by Pedersen and Ronningsen [4] embedded in the industry standard fluid and flow simulator for wax deposition modelling namely PVTsim ® by CALSEP, Multiflash ® by KBC and OLGA ® by Schlumberger which are widely used by the FA fraternities, and additionally evaluate its impact to wax deposition modelling specifically for Malaysian waxy crude oil applications. Rheological experiments were run for six Malaysian waxy crude oil samples and used for this evaluation. The application of the Pedersen and Ronningsen model for wax deposition modelling is demonstrated using the widely accepted Matzain Model [5].

As highlighted in various published papers, methods to fit experimental viscosity data into the viscosity model for wax deposition modelling were not explicitly discussed. Rather, wax deposition modelling was performed by tuning or fitting of empirical constants in matching experimental and field wax deposition data, assuming accurate viscosity prediction using the viscosity model [2,3,6,7]. Viscosity prediction inaccuracy could lead to wax deposition prediction errors that would contribute to substantial risk in wax management especially when flow simulators are used to troubleshoot issues at the field [10]. Soedarmo et al. [2] in their paper, validated a few wax deposition models using 70 wax deposition data points from 19 different conditions and concluded that to improve modelling prediction uncertainties, better measurements of wax precipitation and viscosity are required.

It is generally summarized that current deposition models may not be able to provide reliable predictions on long-term wax deposition. Design optimization and routine maintenance operations could then be a challenge, hence the need to improve the accuracy of deposition predictions in order to strike a balance between optimal design and economical operations.

2. METHODOLOGY

The investigation is conducted by evaluating the present model performance by comparing the predicted non-Newtonian viscosity profiles which were simulated using Pedersen and Ronningsen model in the fluid simulator, PVTsim, against experimental data sets from six Malaysian waxy crude oil samples. The results are plotted to demonstrate the prediction of wax deposition using various viscosity modelling methods in matching experimental data points. The impact of viscosity predictions on wax deposition modelling are demonstrated in OLGA, a transient multiphase flow simulator.

In general, the major components of wax deposition modelling are thermodynamics, hydrodynamics, heat and mass transfer, and wax deposition mechanism. The temperature and wax concentration profile can be obtained by simultaneously solving the heat and mass transfer equations. Typically, crude oil viscosity is treated as a Newtonian fluid for multiphase flow modelling, however, for wax deposition modelling, when dealing with fluid temperatures below WAT, the effect of the resulting non-Newtonian fluid behaviors has to be considered. This is because, viscosity has considerable impact on wax deposition in the pipeline which is mainly governed by diffusion and shear stripping mechanism.

There are several rheological models published in describing the non-Newtonian waxy crude oil behaviors namely the Bingham model, also called pseudo-plastic [11], the Herschel-Buckley (HB) model, and the Casson model [4], as shown in Eq. (1) to Eq. (3), respectively.

$$\tau = \tau_B + \eta\gamma \ (Bingham) \tag{1}$$

$$\tau = \tau_{HB} + m\gamma^n \ (Herschel - Buckley) \tag{2}$$

$$\sqrt{\tau} = \sqrt{\tau_C} + \sqrt{\eta}\sqrt{\gamma} \ (Casson) \tag{3}$$

where τ is the shear stress (Pa), η is the viscosity (Pa. s) and γ is the applied shear rate (s^{-1}).

Bhaskoro [12] in his work, reviewed the applications of these rheological models for four Malaysian waxy crude oils and concluded that both the Casson model and the HB model can be used to describe the rheological behaviors below WAT of all the crude samples with the latter model generally providing a better fit with R^2=0.9998.The general viscosity model was then developed based on Malaysian crude oil's rheological and wax data based on the HB model and the results presented showcased better performance when compared with viscosity models previously available, as presented in Bhaskoro et al. [13]. However, the model requires additional fluid information i.e., activation energy, which is not readily available from standard testing and applied using current engineering software. It is worth noting that, the Pedersen and Ronningsen model has been widely used by the FA engineers as it is the only model that is readily available in most commercial applications such as PVTsim, Multiflash and OLGA and thus will be the context of this paper.

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Pedersen and Ronningsen [4] stated that the apparent viscosity of the crude oil would increase when wax crystalized and dispersed in bulk oil, which eventually led to an increase in the pressure drop in the pipeline. When the wax particles are available at sufficiently high concentrations, it will change the crude oil flow behavior from Newtonian to non-Newtonian behavior. The transition typically occurs at roughly 10 to 15 ºC below WAT and at solid wax fraction of 1 to 2wt%, but this usually depends on the waxiness/characteristics of the oil. Their first viscosity model was presented based on 713 measured viscosity data points from 18 different gas-free North Sea oils and leveraging the Casson-type rheological fluid model to describe the non-Newtonian behaviors [4]. Review methodology is presented in Fig. 1.

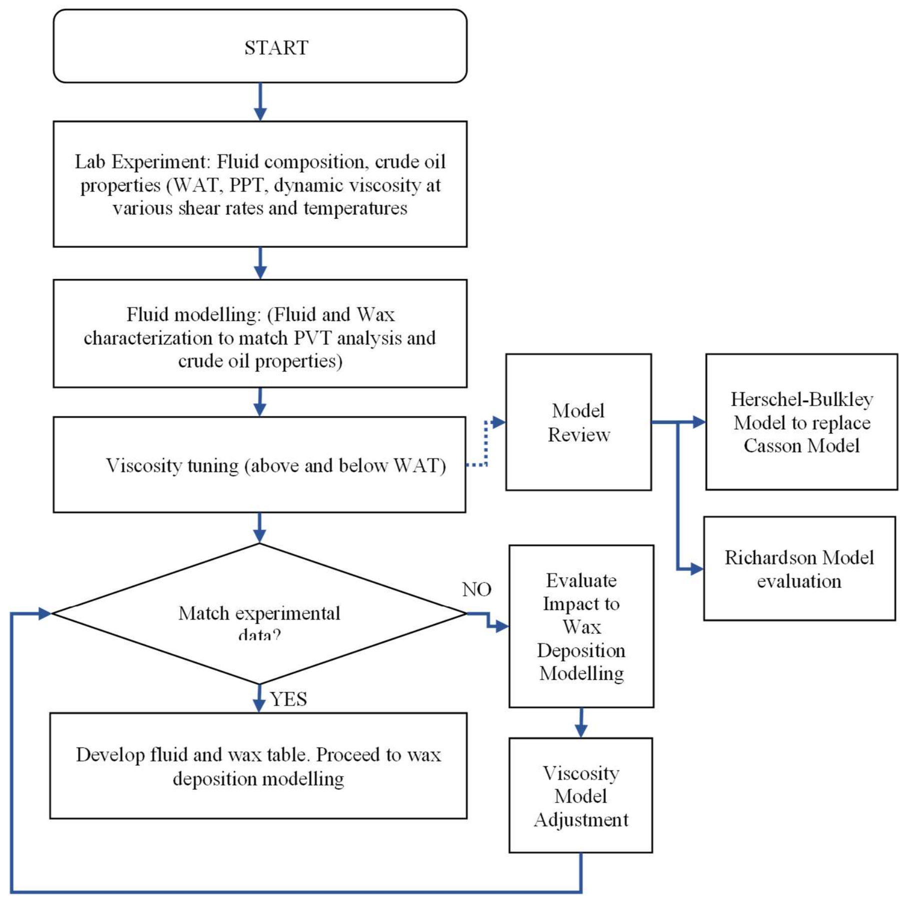

Fig. 1: Review methodology.

2.1 Non-Newtonian Viscosity Measurement

An AntonPaar MCR-302 controlled stress rheometer was used to measure crude oil viscosity covering both Newtonian and non-Newtonian ranges. Cross-hatched parallel plate geometry made of stainless steel with a diameter of 40 mm was used to avoid slippage during measurement. The groove roughness is set higher than 10 μm as suggested by Barnes [14] for a condition where complete adhesion is violated. Similar procedure proposed by Yoshimura and Prud Homme [15] was adopted by which minimal slip effect was achieved.

The crude oil sample, and both lower and upper roughened geometry (the roughened parallel plate), were pre-heated around 10 ºC above the WAT but below 60 ºC to avoid evaporation of light components. Approximately 2 mL of (liquid) crude oil sample was loaded onto the measurement gap set at 500 microns using a pipette. Japper-Jaafar et al., [16] explained that this gap size aims to provide some degree of freedom for the wax crystals' movement and to minimize wall effects. The sample was maintained at the temperature for 5 minutes to ensure complete wax dissolution. Then, viscosity of the sample was measured from approximately 10 ºC above WAT down to 15 ºC at a cooling rate of 0.5 ºC/min and under continuous shear rates of 10 s^{-1}, 50 s^{-1}, 100 s^{-1}, 300 s^{-1}, 500 s^{-1} and 1000 s^{-1}.

The viscosity measurement procedures to ensure accuracy and repeatability in this paper is as per described in Petrus and Azuraien [9]. To address the viscosity measurement reproducibility, the same sample from previous work by Bhaskoro et al., [13] using one of the Malaysian crude oils, Fluid S06 (which is represented as Crude oil A in his paper) was used for the current study. Temperature dependent-viscosity measurements for crude oil A were conducted using a controlled stress rheometer AR-G2 and DHR-1 from TA instrument while the current study uses other equipment which is an AntonPaar MCR-302 rheometer in a different laboratory. A log scale plot is presented in Fig. 2 to demonstrate the viscosity trends based on current and previous works.

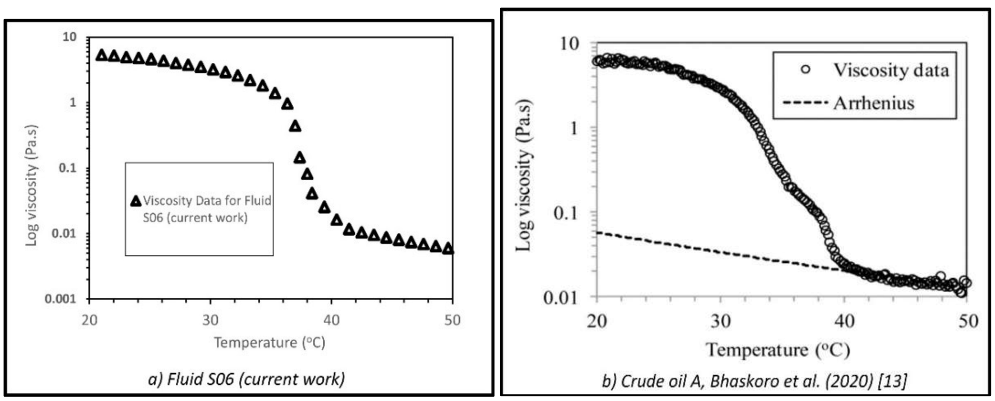

Fig. 2: Viscosity measurement reproducibility test.

Fig. 2 compares viscosity measurement from a) current work and b) previous work as presented in Bhaskoro et al., [13] that gives the same trend of instantaneous steep change of viscosity trends below WAT and PPT. Additionally, Petrus and Azuraien [9] observed similar trend when conducting rheological measurement for a waxy crude oil from the South East Asia region, as presented in Fig. 2 and Fig. 3 in their paper .

2.2 Non-Newtonian Viscosity Modelling

In general, the viscosity model by Pedersen and Ronningsen [4] has been incorporated in PVTsim, Multiflash and OLGA, however, in PVTsim, the viscosity model has been modified using proprietary data from Statoil [17].

The apparent viscosity of oil with suspended wax particles (a shear-rate-dependent viscosity model) is calculated as follows,

$$\eta = \eta_{liq}\left[exp(D.\theta_{wax}) + \frac{E.\theta_{wax}}{\sqrt{\frac{dv_x}{dy}}} + \frac{F.\theta_{wax}^4}{\frac{dv_x}{dy}}\right] \tag{4}$$

where η_{liq} is the viscosity (Pa.s) of the oil not considering solid wax and $Ø_{wax}$ the volume fraction of the precipitated wax in the oil-wax suspension, dv_x/dy is the shear rate (s^{-1}), and the empirical constant/parameters D, E, F will have the following values: D = 37.82, E = 83.96, and F = 8.559 x 10^6 (shear rates in s^{-1}) [18]. Calculation of the viscosity of the wax/oil dispersion in OLGA and Multiflash simulators assumed the model directly proposed by Pedersen and Ronningsen [4].

PVTsim software, assumed a similar model by Pedersen and Ronningsen, where it has, however, been modified in 2006 using proprietary data from Statoil. The empirical constant/parameters D, E, F in Eq. (4) will have the following values: D = 18.12, E = 405.1, and F = 7.876 x10^6 (viscosities in mPa.s and shear rates in s^{-1}) [17].

Pedersen and Ronningsen further presented a new viscosity model with empirical constants D, E, F that accounts for wax inhibitors effect based on 12 different commercial wax crystal modifiers [19]. The empirical constants used in this case are D = 22.42, E = 1189, and F = 1.335 x 10^6 (viscosities in mPa.s and shear rates in s^{-1}). It should be noted that the study suggests that the inhibitors used only have marginal influence on the amount of solid wax formed but do exhibit pronounced effect on pour point and apparent viscosity, especially in the temperature interval from around 10 to 25 ºC. The effect of the inhibitors on viscosity can be modelled by assigning to wax molecules in the range of C21 to C45 a lower melting temperature in the presence of wax inhibitors than that without.

In the current modelling practice, the wax-oil viscosity behavior is modelled and regressed in fluid simulators (i.e., PVTsim and Multiflash) to match the measured viscosity data for oil with suspended wax at different shear rates. The wax multipliers/correction factors are then applied to calculate the final wax viscosity multipliers using Eq. (5) to (7) which are served as input into OLGA or any other flow simulator when using the Matzain wax deposition model using input keys of VISCMULTD, VISCMULTE and VISCMULTF [17]. This correction is needed to account for different wax viscosity models used by different software (in this case, OLGA and PVTsim):

$$VISCMULTD_{OLGA} = VISCMULTD_{PVTsim} \times \frac{D_{PVTsim}}{D_{OLGA}} \tag{5}$$

$$VISCMULTE_{OLGA} = VISCMULTE_{PVTsim} \times \frac{E_{PVTsim}}{E_{OLGA}} \tag{6}$$

$$VISCMULTF_{OLGA} = VISCMULTF_{PVTsim} \times \frac{F_{PVTsim}}{F_{OLGA}} \tag{7}$$

It should be additionally noted that this is only applicable when transferring multipliers from PVTsim to OLGA. The D, E, F empirical constants/parameters used by all software are tabulated in Table 1. In OLGA, shear rates are simulated and serve as input for the apparent oil viscosity calculation (4) to account for suspended wax particles.

Table 1: D, E, F empirical constants in Fluid and Flow Simulators

D,E,F Constants	OLGA/ Multiflash	PVTSIM
D	37.82	18.12
E	83.96	405.1
F	8.56 X 10^6	7.876 X 10^6

2.3 Matzain Wax Model

The Matzain wax model is a widely used wax model and it is available in most commercial multiphase flow simulators for industry applications. Even though few wax deposition models have been introduced and enhanced since the first time the Matzain Wax Model was developed more than 20 years ago, the investigation uses the Matzain Wax Model which has been reported to be effective in estimating wax deposition based on multiple validation works [2,7,18].

The Matzain Wax Model [5] is a semi-empirical model based on the Equilibrium model (EM) which considers molecular diffusion and shear stripping mechanism in predicting wax deposition. The kinetic wax deposition model is described as below:

$$\frac{d\delta}{dt} = \frac{\pi_1}{1+\pi_2} D_{ow} \left[\frac{dC_w}{dT}\frac{dT}{dr}\right] \tag{8}$$

$$D_{ow} = 7.4x10^{-8} \frac{T_w(\psi MW)^{0.5}}{\mu_{o,f} V^{0.6}} \tag{9}$$

where, δ is the thickness of wax layer deposited on the wall (m), D_{ow} is the diffusion coefficient evaluated at the wax-oil/gas interface using Wilke and Chang correlations [21] in Eq. (9), C_w is the concentration of wax in solution (weight %), r is the pipe radial distance (m) and T is the fluid temperature (°C). In Eq. (6), ψ is the oil association parameter assumed equal to 1.0 and recommended for a crude oil system. D_{ow} is in cm^2/s, $\mu_{o,f}$, which is the viscosity of wax-oil in mPa.s and wax molar volume (V) is in cm^3/mol.

π_1 is an empirical correlation introduced to account for the porosity effect on the rate of wax build up and for other deposition enhancement mechanisms not considered by the diffusion mechanism alone (e.g., turbulent mass diffusion mechanism) as shown in Eq. (10) below,

$$\pi_1 = \frac{C_1}{1-{C_L}/{100}} \tag{10}$$

$$C_L = 100\left(1 - \frac{{N_{Re,f}}^{0.15}}{8}\right) \tag{11}$$

where, C_L describes the amount of oil trapped in the wax layer and $C_1 = 15$.

The dimensionless parameter $N_{Re,f}$ is a function of the effective inside radius of the pipeline and is evaluated at the wax-oil/gas interface as shown in Eq. 12, where ρ_{oil} is the density of oil in kg/m^3, v_{oil} is oil velocity in m/s, d_w is the effective inside pipe diameter as a result of wax build-up in m and μ_o is the viscosity of oil in mPa.s.

$$N_{Re,f} = \frac{\rho_{oil} v_{oil} d_w}{\mu_{oil}} \tag{12}$$

π_2 accounts for the wax limiting effect due to shear stripping and is defined as below:

$$\pi_2 = 1 + C_2\, {N_{SR}}^{C_3} \tag{13}$$

where $C_2 = 0.055, C_3 = 1.4$

The flow regime dependent Reynolds number (N_{SR}) is calculated for each regime as shown below:

For single phase and stratified wavy flow:

$$N_{SR} = \frac{\rho_{oil} v_{oil} \delta}{\mu_{o,f}} \tag{14}$$

For bubble and slug flow:

$$N_{SR} = \frac{\rho_{mix} v_{oil} \delta}{\mu_{o,f}} \tag{15}$$

For annular flow:

$$N_{SR} = \frac{\sqrt{\rho_{mix}\rho_{oil}}\, v_{oil} \delta}{\mu_{o,f}} \tag{16}$$

The above expressions demonstrated that the wax deposition thickness profiles in pipeline according to the Matzain wax deposition model, have been modelled as dependent on the wax deposition mechanisms, flow conditions and flowing fluid properties, including oil viscosity and wax-oil viscosity. Wax-oil viscosity here refers to wax-oil suspension viscosity and this property is evaluated at the wax-oil/gas interface based on the Matzain Model [5].

Soedarmo et al., [2] presented wax deposition model's performance using Film Mass Transfer (FMT) and Equilibrium Model (EM) which can be affected by viscosity input as presented in Fig. 3, included in their paper.

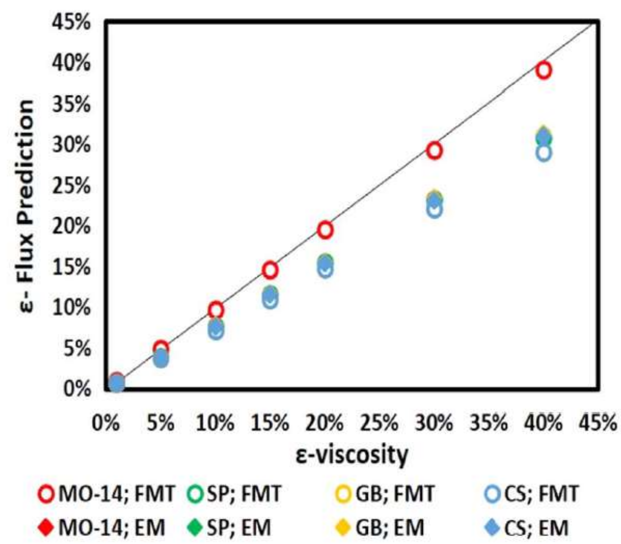

Fig. 3: Wax Mass Flux Prediction Errors: FMT and EM model sensitivity to uncertainties in viscosity.

As viscosity plays major roles in wax deposition predictions, it is crucial to get accurate predicted values from the viscosity model, to ensure accurate wax deposition modelling for field consumption. The traditional approach in tuning the deposition model is for the simulation models to match wax deposition tests which are ideally conducted using large or smaller scale pipeline tests at laboratory, also called flow loop. However, due to the cost associated with the test, often, it is not conducted, and empirical constants in the deposition models were fitted to match field data (e.g., temperature, pressure). Without further understanding on how the waxy crude oil deposit, model fittings could introduce unphysical behavior. To reduce the wax deposition modelling fitting ranges and uncertainties, it is prudent to identify the effect of each parameters used and to evaluate methods to eliminate tuning uncertainties, which in this case is focusing on the application of present non-Newtonian viscosity model for Malaysian waxy crude oils.

3. CASE STUDY ON MALAYSIAN WAXY CRUDE OILS

3.1 Materials

Six (6) waxy crude oil samples from Malaysian fields are used for this study. The basic properties measured are tabulated in Table 2 as below. Three data sets (Fluid D02, Fluid S06, and Fluid D01a) will be used to showcase viscosity prediction via modelling (covering fluid and flow simulations) and all six data sets will be used to showcase Malaysian waxy crude oils' viscosity measurements and behaviors.

Table 2: Fluid experimental data sets

Crude Oil Samples	Wax Appearance Temperature (°C)	Pour Point Temperature (°C)	Wax Content (wt%)
Fluid D01a[a]	37	17	20
Fluid D02	44	33	7.6
Fluid D01b[a]	40	27	18.3
Fluid W101	43	36	15.5
Fluid W103	36.5	18	11.4
Fluid S06	49.5	39	26.7

[a] Fluid D01a and Fluid D01b are fluids taken from commingling header; Fluid D01a has been added with Pour Point Depressant while other fluids in this list are blank waxy crude oil samples directly from the wells.

For the purpose of wax deposition modelling, the viscosity impact will be evaluated mainly from non-Newtonian rheological behaviors perspective (below WAT). Experimental viscosity data at various shear rates for the above crude oils are plotted in Fig. 4, Fig. 5, Fig. 6**Error! Reference source not found.**, Fig. 7, Fig. 8, and Fig. 9 respectively. The shear rates for specific crude oil are determined based on pipeline size and production rates accordingly.

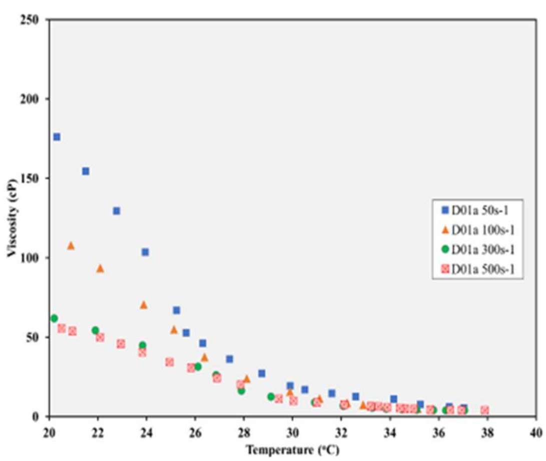

Fig. 4: Experimental viscosity data below WAT for Fluid D01a at various shear rates.

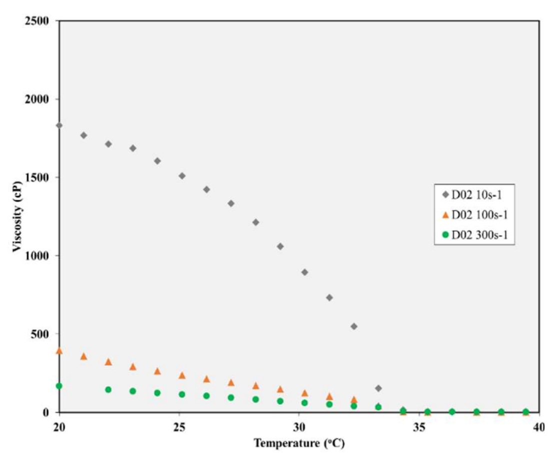

Fig. 5: Experimental viscosity data below WAT for Fluid D02 at various shear rates.

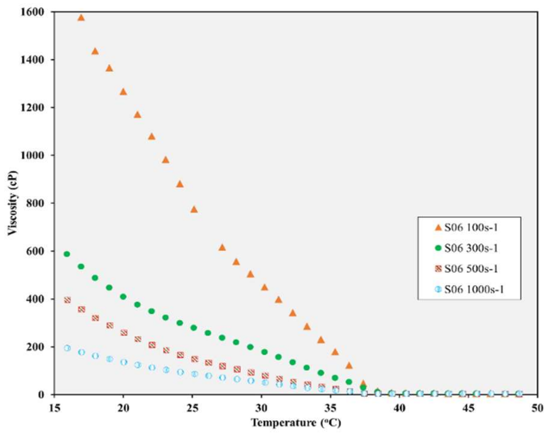

Fig. 6: Experimental viscosity data below WAT for Fluid S06 at various shear rates.

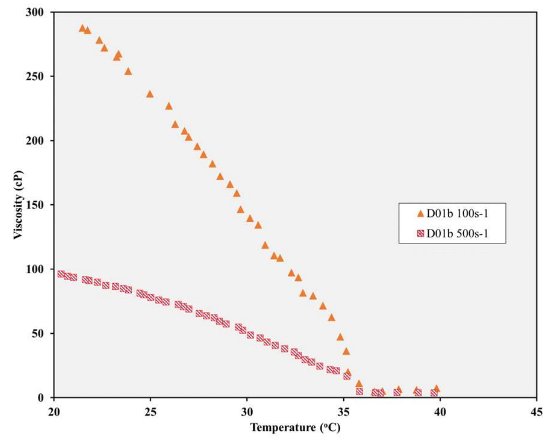

Fig. 7: Experimental viscosity data below WAT for Fluid D01b at various shear rates.

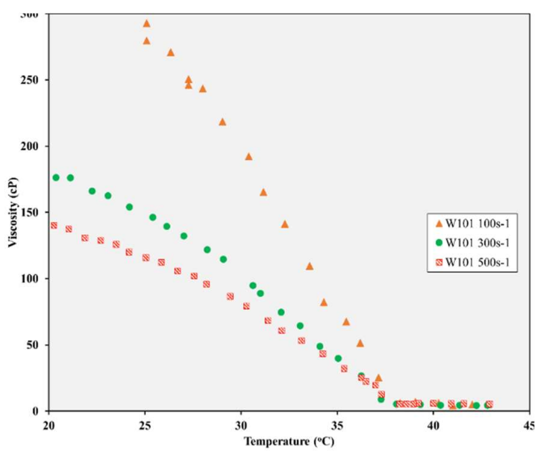

Fig. 8: Experimental viscosity data below WAT for Fluid W101 at various shear rates.

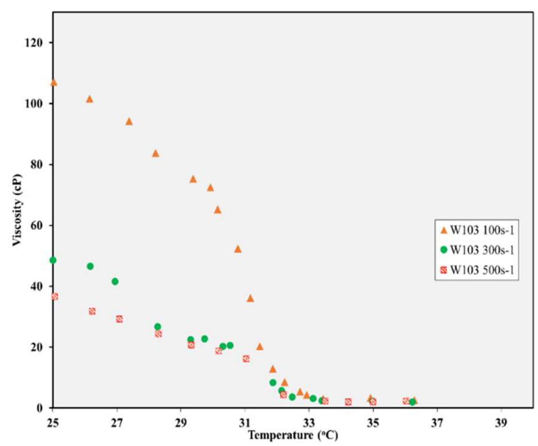

Fig. 9: Experimental viscosity data below WAT for Fluid W103 at various shear rates.

Additionally, three (3) material parameters; τyo, k and n, as a function of temperature are presented in Table 3 for Fluid S06.

Table 3: Herschel-Bulkley parameters obtained at various temperatures after dynamic cooling at 1 °C/min for Fluid S06

T (°C)	τ_{yo} (Pa)	k (Pa.s)	n
55	0	0.00305	1
52.5	0	0.00324	1
50	0	0.00371	1
47.5	0	0.00414	1
45	0	0.00478	1
42.5	0	0.00534	1
40	0.2	0.0007	0.973
37.5	15.5	0.0699	0.9794
35	16.2	0.253	0.9374
32.5	22	0.2462	0.9184

30	25	0.4012	0.9199
27.5	26.5	0.5767	0.9099
25	30	0.9118	0.906
22.5	32	1.0201	0.9158
20	40.3	1.7515	0.8733

4. RESULTS AND DISCUSSION

4.1 Regression of Viscosity Model to fit Experimental Data

Prior to viscosity tuning in PVTsim, fluid and wax characterization activities were performed on each fluid to match the experimental dataset comprising of GC (gas chromatography), PVT data (pressure volume temperature), n-paraffin distribution, wax content, WAT, and crude oil properties. In general, tuning enables the viscosity model to match the given experimental data at specific shear rates and temperature ranges. This is done in fluid simulators by adjusting wax viscosity multipliers/correction factors manually through a trial-and-error method. The tuning process was repeated until it matched the experimental data.

4.2 Impact of non-Newtonian viscosity on Wax Deposition Modelling

Equations (8) to (16) from Matzain model demonstrates how viscosity plays roles in determining the wax deposition thickness profile in pipelines. Since wax deposition is a function of wax deposition mechanisms, flow regime, and many other factors, to enable direct evaluation of the impact of non-Newtonian viscosity model to wax deposition thickness, the OLGA runs will focus on simulating the diffusion coefficient, D_{ow}, as it has a direct inverse effect to wax-oil viscosity on top of evaluating general impact to wax mass (net effect). Viscosity tuning below WAT in matching experimental data are achieved using either automatic or manual tuning and the impact to wax deposition will only be demonstrated for three (3) fluids: Fluid D01a, Fluid D02 and Fluid S06, since Fluid D01b, Fluid W101 and Fluid W103 are produced from the same field but from different reservoirs.

Flow loop models were constructed in OLGA to showcase the impact on the viscosity model predictions in flow simulators. The Matzain model is used, and wax deposition tuning factors are kept as default. The goal is to simulate wax deposition modelling and evaluate the impact of applying different viscosity multipliers. Tuning to wax deposition tests is currently not considered for this work. To demonstrate the immediate effect of viscosity multipliers to wax deposition, departing fluid temperatures are set to below WAT. Additionally, it is worth noting that VISHL, which is the effective viscosity including the non-Newtonian wax effect, is determined at fluid temperature in OLGA.

4.2.1 Fluid D01a – Viscosity Behavior Transition 4 °C below WAT

Dashed lines in Fig. 10 represent the viscosity predictions using the Pedersen and Ronningsen model based on various tuning methods. For Fluid D01a, automatic viscosity tuning at various shear rates (Set 3) returned a good matching to experimental data only at higher shear rates of 500 s^{-1} and at higher temperatures. Manual tuning on viscosity at various shear rates (Set 1) showed improvement in viscosity predictions however, they still suffer underprediction of up to 2 times, especially at low temperature ranges. D, E, F wax viscosity multipliers/correction factors are presented in Table 4. Better match to measured viscosity data is achieved with (Set 2) which was selected as the basis for wax deposition modelling.

Fluid D01a flows from Field Y through a 10-km pipeline with seabed temperatures ranging from 26 ºC to 30 ºC and at shear rates of 100 s^{-1} and lower. To enable correct representation of the viscosity profile for Fluid D01a, the viscosity model is manually adjusted to match experimental shear rates at 50 s^{-1} and 100 s^{-1} (Set 2) matching the pipeline shear rates. Manual tuning enabled matching to the lowest operating temperature of 26 ºC and higher.

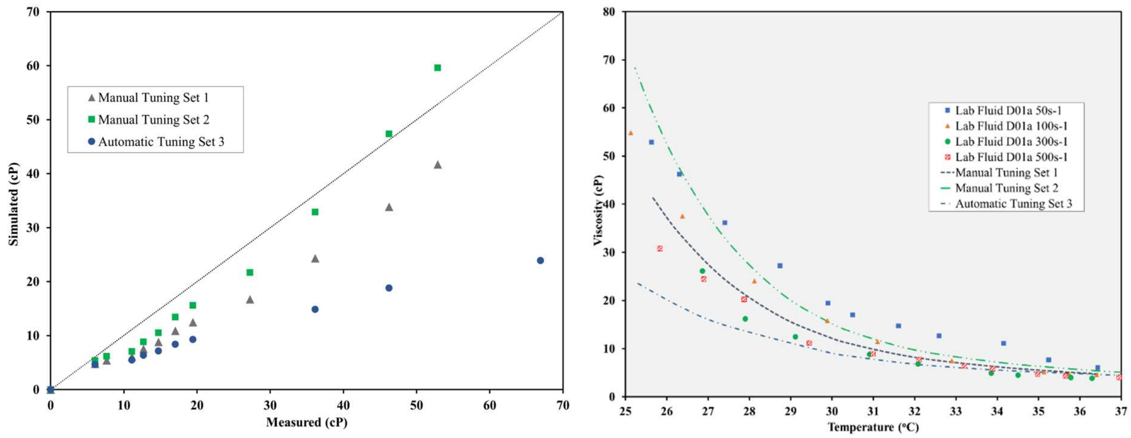

Fig. 10: Tuned viscosity below WAT at 50 s^{-1} for Fluid D01a using various tuning methods.

Table 4: Viscosity Multipliers/Correction Factors used in OLGA for Fluid D01a

Viscosity Multipliers /Correction Factors	Manual Tuning at Various Shear Rates (Set 1)	Manual Tuning at Specific Shear Rates/ Temperature (Set 2)	Automatic Tuning at Various Shear Rates (Set 3)
D	0.292	1.437	0.767
E	5.675	0	0
F	3.030	0.575	0.575

In OLGA, a 0.25-inch and 1-meter flow loop model with fluid departing temperature of 30 ºC (below WAT), seabed ambient temperature of 26 ºC and a mass flow of 21 kg/s have been specified as mass source. The fluid D, E, F wax viscosity multipliers used in OLGA after tuning in PVTsim are as per Table 4. Fig. 11 presents the wax mass (net effect) using three different sets of wax viscosity multipliers, and the Apparent Wax Diffusion Coefficient for oil/wax dispersion, D_{ow} is tabulated in Table 5.

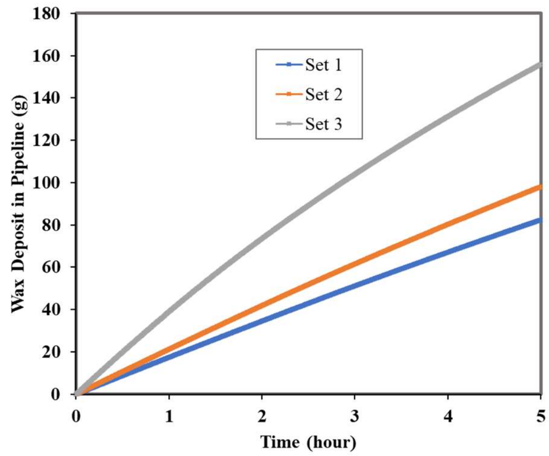

Fig. 11: Wax deposit mass in branch predicted in OLGA using various viscosity tuning methods based for Fluid D01a.

Table 5: Wax deposition modelling results using different viscosity multipliers for Fluid D01a

Simulation Run (5-hours)	Wax Mass (gram)	Apparent Wax Diffusion Coefficient (m^2/s)	Predicted Viscosity	Impact to Wax Mass
Set 1	82.31	5.592×10^{-11}	Higher viscosity	-15.97% Error
Set 2	97.95	6.312×10^{-11}	Baseline (Proposed tuning)	
Set 3	155.77	9.717×10^{-11}	Lower viscosity	+59.03% Error

Table 5 summarizes the impact of various viscosity multipliers on wax deposition prediction. We can observe significant increase up to 59% in wax deposition prediction using automatic tuning (Set 3), which tends to underpredict the viscosity, and 16% reduction using manual tuning at various shear rates (Set 1) when compared to Set 2. The results showed that underprediction on viscosity value will give high wax deposition mass and vice versa. In this case, set 2 has been used as baseline since it provides the best match with experimental data at the respective pipeline shear rates and temperatures.

4.2.2 Fluid D02 – Viscosity Behavior Transition 10 ^oC below WAT

Fluid D02 was initially tuned in PVTsim at all shear rates (automatic tuning) and the simulated wax viscosity multipliers are VISCMULTD = 0, VISCMULTE = 0 and VISCMULTF = 0.5632. The zero values indicated that the value is not found to be sensitive to any further tuning. It can be observed from Fig. 12 that after tuning to experimental data, Fluid D02 is still unable to accurately match experimental data at all shear rates, especially at low shear rate, therefore tuning is conducted based on one interested shear rate most potentially experienced by the pipeline. The interested shear rate is calculated using pipeline flowrates and geometries.

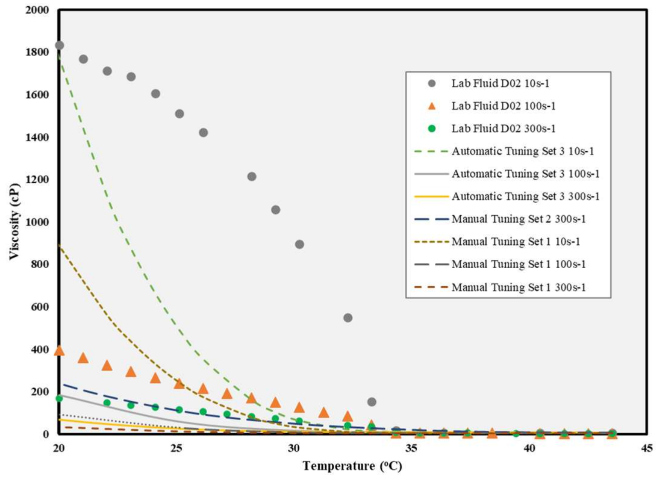

Fig. 12: Tuned viscosity below WAT at various shear rates for Fluid D02 using various tuning methods.

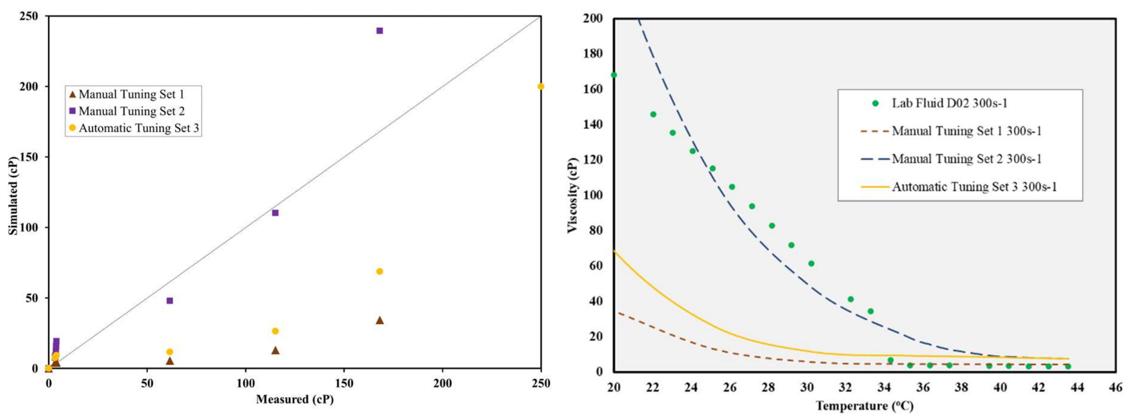

Fig. 13: Tuned Viscosity below WAT at 300 s^{-1} for Fluid D02.

After tuning, present model showcased an underprediction of viscosity up to 4 times (refer to Fig. 13), which is beyond 100% error, especially at operating fluid temperature of below pour point of 33 ºC. Additionally, it can be observed that present viscosity model has not able to match the transition region between 33 ºC to 40 ºC. For Fluid D02, the average seabed ambient temperature experienced by the pipeline is 22 ºC, hence it is critical to get the viscosity model to match experimental data, especially at the lower temperature ranges.

Table 6: Viscosity Multipliers/Correction Factors used in OLGA for Fluid D02

Viscosity Multipliers /Correction Factors	Manual Tuning at Various Shear Rates (Set 1)	Manual Tuning at Specific Shear Rates/ Temperature (Set 2)	Automatic Tuning at Various Shear Rates (Set 3)
D	0	0	0
E	0	12.062	0
F	0.5182	1.251	1.183

A 1.75-inch and 3-meter model is constructed in OLGA, with departing temperature at 40 ºC (below WAT), seabed temperature of 22 ºC and a mass flow of 0.513 kg/s which were specified as mass source. The D, E, F wax viscosity multipliers used in OLGA after tuning in PVTsim are as per Table 6. Field Z flows Fluid D02 at a shear rate of 300 s^{-1} and a minimum seabed temperature of 22 ºC as described. Fig. 14 presents the Wax Mass (net effect) at three different sets of viscosity multipliers, and the Apparent Wax Diffusion Coefficient for oil/wax dispersion, D_{ow} is tabulated in Table 7.

As per Fig. 12 and Fig. 13, it is anticipated that both automatic (Set 3) and manual tuning of viscosity data at all shear rates (Set 1) would return a much lower viscosity predictions, which would return a high wax mass (up to 336%), as summarized in Table 7, and are in agreement with previous results. Manual tuning of Set 2 improved viscosity predictions for viscosity below 150 cP as presented in Fig. 13.

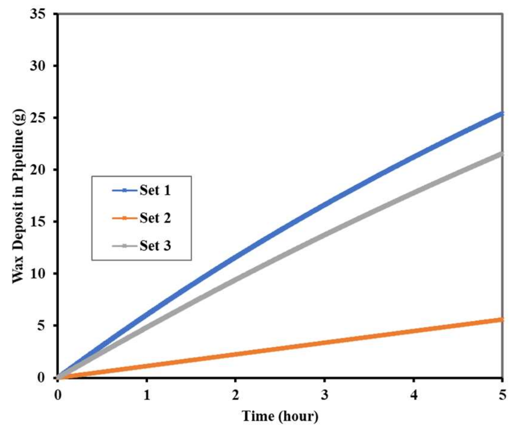

Fig. 14: Wax deposit mass in branch predicted in OLGA using various viscosity tuning methods based for Fluid D02.

Table 7: Wax deposition modelling results using different viscosity multipliers for Fluid D02

Simulation Run (5-hours)	Wax Mass (gram)	Apparent Wax Diffusion Coefficient (m^2/s)	Predicted Viscosity	Impact to Wax Mass
Set 1	29.34	6.25×10^{-11}	Lower viscosity	+336.61% Error
Set 2	6.72	1.12×10^{-11}	Baseline (Proposed tuning)	
Set 3	25.18	4.98×10^{-11}	Lower viscosity	+274.70% Error

4.2.3 Fluid S06 – Viscosity Behavior Transition 15 ºC below WAT

A more comprehensive data set is presented for Fluid S06. Viscosity measurement is conducted at shear rates of 1000 s^{-1},500 s^{-1}, 300 s^{-1}, and 100 s^{-1}. The fluid was initially tuned in PVTsim at both shear rates (automatic tuning) and the resultant wax viscosity multipliers are VISCMULTD = 0.5867, VISCMULTE = 0.2271 and VISCMULTF = 2.6581. Generally, at higher shear rates (more than 500 s^{-1}), the Pedersen and Ronningsen model is able to match experimental data at most points, however at lower shear rates of 100 s^{-1}, 300 s^{-1}, and especially below Fluid S06 pour point of 39 ºC, the model showcased an underprediction of up to 7 times. Manual tuning is conducted based on one interested shear rate (shear rate of 1000 s^{-1}) and is presented in Fig. 15.

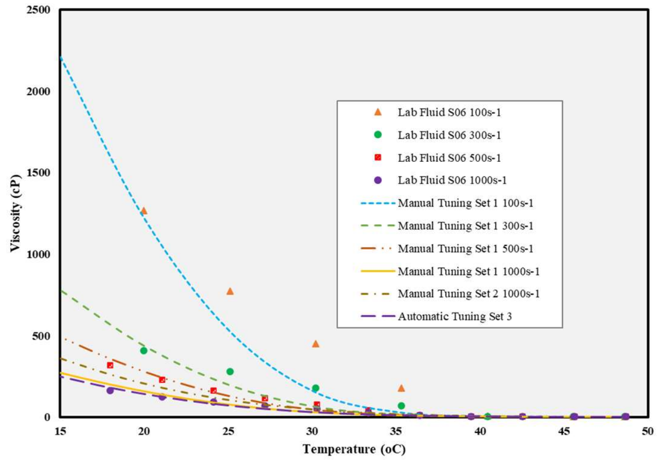

Fig. 15: Tuned viscosity below WAT for Fluid S06 using various tuning methods.

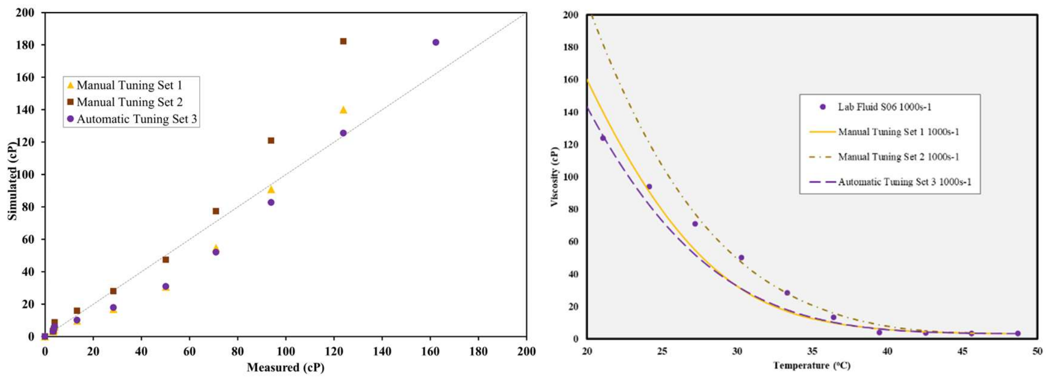

Fig. 16: Tuned Viscosity below WAT at 1000 s^{-1} for Fluid S06.

Fig. 16 showcases better predictions when fluid was tuned to specific shear rate of 1000 s^{-1} with a lower underprediction (less than 2 times) when compared to tuning at various shear rates in Set 1 and Set 3 (7 times). Manual tuning was performed to get a better match at a specific operating temperature range and shear rate. Even using manual tuning, the tuned models were not able to match experimental data at temperatures below 27 ºC accurately, and for immediate field application, the overprediction of viscosity could have an impact in terms of wax deposition as well as pressure drop in the pipeline, and this is deemed to be unacceptable.

Field X flows fluid S06 in a 7 km pipeline with seabed ambient temperature ranging from 22 ºC to 30 ºC. It is predicted that impact on wax deposition will be more apparent when ambient temperature drops below 27 ºC, but in the case of Fluid S06, due to fluid flowing at high shear rates, the impact to wax deposition is predicted to not be as significant. A 0.25-inch and 1-meter model was constructed in OLGA with departing temperature of 40 ºC, seabed temperature of 22 ºC and a mass flow of 0.02 kg/s were specified as mass source. The fluid D, E, F viscosity multipliers used in OLGA after tuning in PVTsim are as follows.

Table 8: Viscosity Multipliers/Correction Factors used in OLGA for Fluid S06

Viscosity Multipliers /Correction Factors	Manual Tuning at Various Shear Rates (Set 1)	Manual Tuning at Specific Shear Rates/	Automatic Tuning at Various

		Temperature (Set 2)	Shear Rates (Set 3)
D	0.281	0.552	0.513
E	1.337	11.160	0.914
F	2.446	0	0

Field X flows Fluid S06 at higher shear rates of 1000 s^{-1} and minimum seabed temperature ranges of 22 ºC. It is expected that the impact of applying different sets of viscosity multipliers would not be apparent as the Pedersen and Ronningsen model can match fairly well at high shear rates. Fig. 17 presented the Wax Mass (net effect) at three different sets of viscosity multipliers, and the Apparent Wax Diffusion Coefficient for oil/wax dispersion, D_{ow} is tabulated in Table 9.

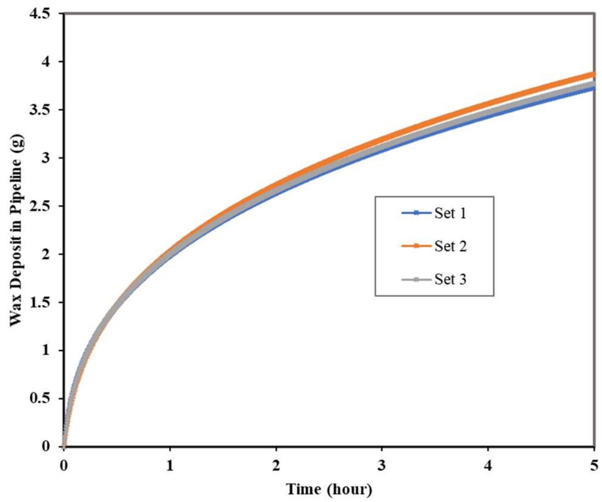

Fig. 17: Wax deposit mass in branch at different wax viscosity multipliers as predicted in OLGA based on the Matzain Wax Model at different viscosity multipliers for Fluid S06.

Table 9: Wax deposition modelling results at different viscosity multipliers for Fluid S06

Simulation Run (5-hours)	Wax Mass (gram)	Apparent Wax Diffusion Coefficient (m^2/s)	Predicted Viscosity	Impact to Wax Mass
Set 1	4.210	2.09×10^{-11}	No significant difference at high shear rates	
Set 2	4.370	1.62×10^{-11}		
Set 3	4.259	1.93×10^{-11}		

It is concluded that since fluid flows at higher shear rates, the impact of different viscosity multipliers will not be as significant as compared to lower shear rates. In this case, the present model deemed to be acceptable.

4.3 Suitability of Present Model on Malaysian Waxy Crude Oil Applications

The Pedersen and Ronningsen model was developed based on viscosity data of 18 North Sea oils (API gravity ranging from 23.8 to 47.6), measured at temperatures between 40 and 0 ºC, and shear rates ranging from 30 s^{-1} to 500 s^{-1}. The model incorporated the Casson rheological model as per Eq. (3) which has been found to represent the equilibrium flow properties of waxy oils very well at high shear rates (up to 700 s^{-1}) and the Richardson viscosity model to describe Newtonian behavior based on analogy from the oil/water emulsion system [4].

As per Fluid S06 review, generally at higher shear rates (more than 500 s^{-1}), the Pedersen and Ronningsen model is able to match experimental data at most points, however at lower shear rates of 100 s^{-1} and 300 s^{-1} and especially below Fluid S06 pour point of 39 ^{o}C, the model showcased an underprediction of up to 7 times. This is because high shear can continuously destroy wax particles and network leading to much smaller wax aggregates or crystals. It makes the fluid have slurry-like behavior which is found to be similar to that observed in the water/oil emulsion system, which is included in the Pedersen and Ronningsen model to describe the Newtonian behavior of the fluid [4].

As per Malaysian crude oil data sets earlier depicted in Table 2 and Fig. 4 to Fig. 9, Malaysian waxy crude oils of higher WAT and PPT tend to exhibit an instantaneous steep change of viscosity trends below WAT and PPT which does not follow the general relationship as described by the Pedersen and Ronningsen model. One hypothesis that can be acknowledged from previous study is that rheological data from Malaysian waxy crude oils were well-described using HB model [12], hence viscosity prediction using the present model could potentially suffer from inaccuracy mainly due to incorporation of the Casson rheological model instead of the HB model. To test this hypothesis, the HB model is fitted into the present model and its performance is further evaluated as below:

The first term is the viscosity which is defined as ratio of shear stress to shear rate.

$$\tau_{xy} = \eta\left(\frac{dVx}{dy}\right) \tag{17}$$

Eq. (17) is integrated into Eq. (2) giving a Herschel-Bulkley model presented as below:

$$\eta_c \frac{dV}{dy} = \tau_0 + k\left(\frac{dV}{dy}\right)^n \tag{18}$$

Assuming that $\tau_0 = \eta_{liq}{\theta_{wax}}^4$, $k = \eta_{liq}\theta_{wax}$ and n = Gθ_{wax} and by applying Richardson model, Eq. (19) may be re-written into a new equation as below,

$$\eta = \eta_{liq} exp(D\theta_{wax})\left(\frac{F{\theta_{wax}}^4}{{dV}/{dy}} + E\theta_{wax}\left(\frac{dV}{dy}\right)^{G\theta_{wax}-1}\right) \tag{19}$$

where G is the additional viscosity multiplier. It is worth highlighting that Eq. (2) as described in Pedersen and Ronningsen [4] as the original model, is not exactly the same with what is described as Eq. (20) in Pedersen [19]. In this case study, performance from both equations will be evaluated.

Pedersen [19] presented a new Eq. (20) to describe viscosity behavior below WAT. Equation (21) is extended to include the HB rheological model.

$$\eta = \eta_{liq} exp(D.\theta_{wax})\left[1 + \frac{E.\theta_{wax}}{\sqrt{\frac{dv_x}{dy}}} + \frac{F.\theta_{wax}^4}{\frac{dv_x}{dy}}\right] \tag{20}$$

$$\eta = \eta_{liq}\left(exp(D.\theta_{wax}) + k.\theta_{wax}\left(\frac{dV}{dy}\right)^{n-1} + \frac{\tau.\theta_{wax}^4}{\frac{dv_x}{dy}}\right) \tag{21}$$

It can be observed from Fig. 18 that even though the HB model has been incorporated to replace the Casson model in the present viscosity model, it is still unable to accurately describe Malaysian waxy crude oil behavior, especially to address the steep change. For this evaluation, the performance of all models is showcased using Fluid S06 at low shear rates of 100 s^{-1}. Additionally, with adjustment, both the Pedersen and Ronningsen model as per Eq. (2) and Eq. (20), performed comparably well as illustrated in Fig. 18 although it shows a big difference at low temperatures.

The second hypothesis that can be deduced is the suitability of the Richardson oil/water emulsion viscosity model embedded in the present model on Malaysian waxy crude oil application. According to Pedersen and Ronningsen model, the Richardson model can be described below [4].

$$\eta = \eta_c exp(D\theta) \tag{22}$$

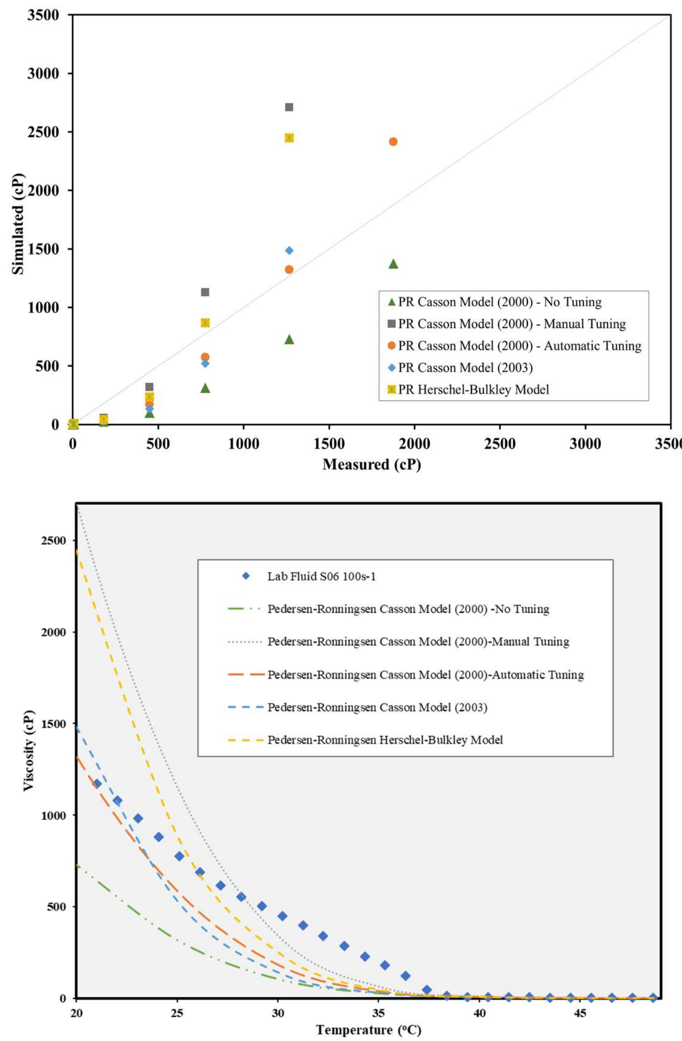

Fig. 18: Viscosity prediction at 100 s^{-1} based on various models.

The Richardson model applies an exponential relationship to define the viscosity of an oil/emulsion, which could be main reason why Malaysian waxy crude oils suffer for over and under-prediction when relying on present viscosity models to describe both Newtonian and non-Newtonian behavior of the fluid. Fig. 19, Fig. 20 and Fig. 21 were plotted to showcase the exponential behavior of the 18 North Sea oils with the highest WAT of 50 ºC and PPT of 32 ºC as listed in Pedersen and Ronningsen model. Sixteen out of 18 data sets show relationship that accurately matched exponential behavior, as described by Richardson and this regression model has been the baseline for the Pedersen and Ronningsen model.

Six Malaysian crude oil viscosity distribution data sets and exponential behaviors are plotted in Fig. 22 and Fig. 23 which generally showcases the behavior of the Malaysian waxy crude oils that do not follow the exponential relationship as described, especially at low shear rates and at temperatures below WAT and close to PPT, therefore, from this observation, it can be concluded that the present model is highly crude-specific and may not be suitable for Malaysian waxy crude oils wax deposition modelling application. Even with the HB model adjustment, modified Pedersen and Ronningsen model is still unable to showcase an acceptable viscosity trend. Due to the steep and instantaneous change of viscosity behavior below WAT and PPT, it is difficult to tune the viscosity model in fluid simulator for the purpose of wax deposition modelling. The present model has not been able to accurately describe the non-Newtonian viscosity behavior for Malaysian waxy crude oils, which in return will impact the accuracy of the wax deposition modelling.

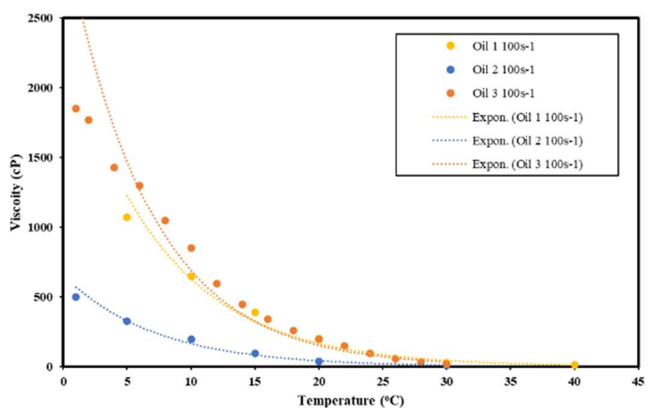

Fig. 19: Viscosity Distribution based on Pedersen and Ronningsen model (Oil 1, Oil 2, and Oil 3).

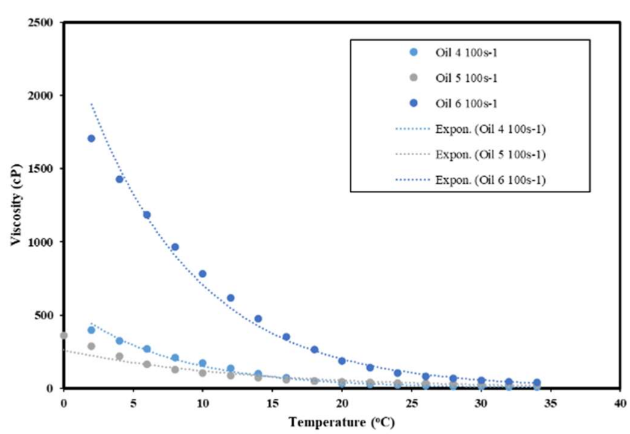

Fig. 20: Viscosity Distribution based on Pedersen and Ronningsen model (Oil 4, Oil 5, Oil 6, and Oil 7)

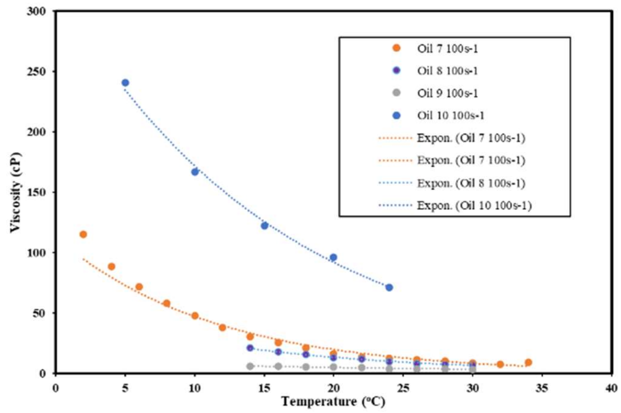

Fig. 21: Viscosity Distribution based on Pedersen and Ronningsen model (Oil 8, Oil 9, and Oil 10).

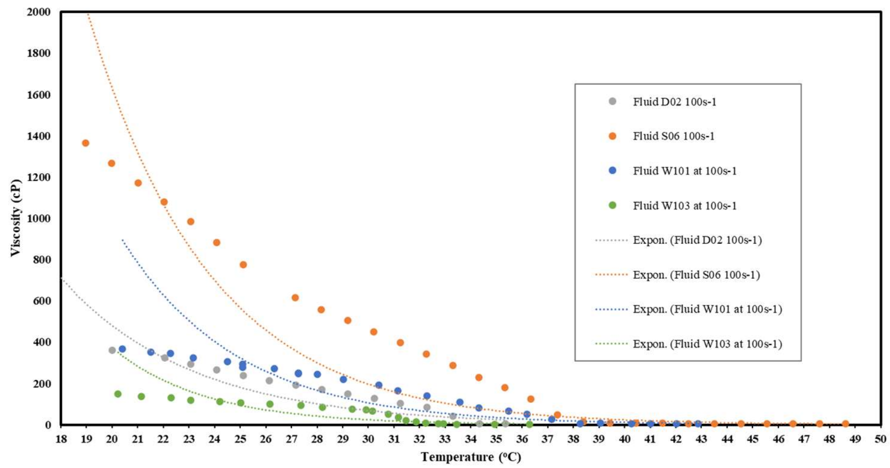

Fig. 22: Viscosity exponential relationship of Malaysian waxy crude at 100 s^{-1}.

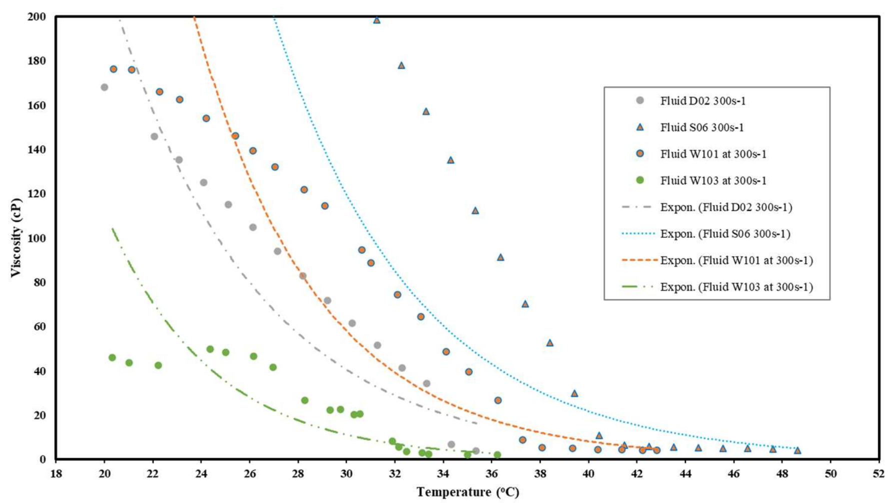

Fig. 23: Viscosity exponential relationship of Malaysian waxy crude at 300 s^{-1}.

https://doi.org/10.31436/iiumej.v24i2.2736

It is worth noting that the present model demonstrates viscosity prediction dependencies to wax content and shear rates, but viscosity of crude oil can be influenced by many other factors including pressure, temperature, crude oil composition and presence of other compounds [20]. The effect of pressure on viscosity of the reservoir fluid is commonly demonstrated as part of PVT testing. With an increase of pressure, viscosity of crude oil reduces which would help in transporting fluid in the reservoir/tubing/pipeline, however it would also incur other risks (e.g., safety when operating at high pressure).

As presented in the Section 3.1, viscosity measurement increases with an increase in temperature, and more prominently as the fluid changes from Newtonian to non-Newtonian region. In fluid flow simulators, wax viscosity is calculated at fluid temperature, hence it is crucial to get a representative thermal-hydraulic flow profile in the pipelines. The limitations of the present model to match Malaysian crude oil experimental data specifically at low temperatures (e.g. up to 4 times underprediction for Fluid D02) would contribute to higher facilities cost to manage wax.

Crude oil composition as well as the other components in the crude oil play the most important roles in viscosity. Santos et al., [20] summarized a few findings from various researchers highlighting the impact of asphaltene concentration on the viscosity, which shows that viscosity can increased sharply with the presence of higher asphaltene content. Malaysian crude oil however, showcased a very low asphaltene content as reported by Sulaimon and Yusoff [8] ranging from 0.13-0.34 wt% which is hypothesized may not have impacted viscosity measurement greatly. It is however a good practice to conduct SARA analysis as part of fluid property screening to determine asphaltene content prior to conducting a more detailed analysis such as dynamic viscosity measurement.

Nevertheless, the present model is deemed to be acceptable when dealing with high shear rates and at higher temperatures as observed in the simulation cases. It is very prudent to determine pipeline specific shear rates, and when dealing with lower ambient temperatures, the prediction error and its impact needs to be accounted for in the decision making.

As a way forward, a more reliable model such as that proposed by Bhaskoro et al., [13] that were developed based on Malaysian waxy crude oil should be used in engineering applications. As described in his paper, above WAT, viscosity of waxy crude oil follows Arrhenius Law, while below WAT, the viscosity deviates from Arrhenius behavior up to several orders of magnitude due to the precipitated wax crystals. The general temperature-dependent viscosity model was developed by modifying the HB model and incorporating the critical physico-chemical properties dictating the viscosity behavior which are activation energy of viscous flow, molecular weight, total wax content, and amount of precipitated wax. The model as described has showcased its superior capability in predicting both Newtonian and non-Newtonian viscosity of the waxy crude oils without rheological data input specifically on its application for waxy crude oils from the Malay basin. The same Malaysian crude oil, Fluid S06 (which is represented as Crude oil A in his paper) has been tested, and its performance is presented below [13]. Generally, Fig. 24, as presented in Bhaskoro et al., [13] shows that the model can match experimental datasets better when compared to the present model available in commercial simulators.

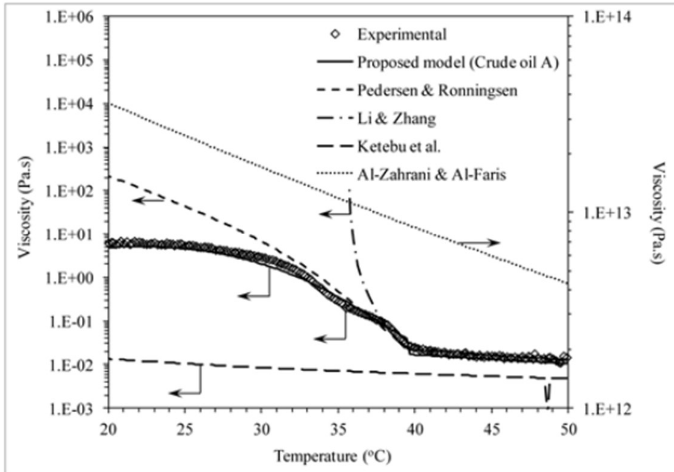

Fig. 24: Performance of Bhaskoro general viscosity model as compared to various published viscosity models.

At the time of this study, however, the said model is not available within the fluid and flow simulators being used. Additionally, although it has modified the exponential terms and developed a generally more suitable model for Malaysian waxy crude oils, this model is still unable to match the viscosity trend specifically at the transition regions (below WAT and close/below PPT).

Ideally, whenever possible, the best way is to enable direct input of measured viscosity data to be used in wax deposition simulation. This can help directly in reducing prediction errors. It should be noted that for pipelines with a high likelihood to experience rapid dynamic changes in flow as well as having wider temperature ranges, the use of the present non-Newtonian viscosity model would not be able to describe the viscosity behavior accurately matching the experimental data. Most of the crude oils shown in this example, are being produced from shallow water depth with a seabed temperature range of 20 to 26 ºC and ambient temperature ranging from 30 to 36 ºC, therefore as a way forward for the wax deposition modelling work, manual tuning is conducted for the viscosity model focusing on tuning at specific temperature ranges and interested shear rates. Additionally, more attention should be given when dealing with viscosity at low shear rates.

5. CONCLUSION

The Pedersen and Ronningsen model is generally unable to accurately describe the non-Newtonian viscosity behavior for the six (6) samples of Malaysian waxy crude oils, especially at low shear rates and low temperatures ranges due to immediate transition/instantaneous change of viscosity behavior below WAT and PPT. From the analysis, it is observed that viscosity prediction inaccuracy could lead to wax deposition prediction error of up to 336%. This would contribute to high risk in wax management especially when flow simulators are used to troubleshoot issues at the field.

Manual tuning is proposed to be performed focusing only on regressing the Pedersen and Ronningsen model to match experimental viscosity datasets at the specific shear rate and specific temperature ranges like what is experienced by the pipelines. Most of the crude oils shown in this paper are being produced from shallow water depth with seabed temperature range of 20 ºC to 26 ºC hence it is critical to match at lower temperature ranges.

Ideally, the best method is to enable direct input of experimental viscosity data sets for the wax deposition modelling hence this feature should be made within current commercial engineering software. Even though that Bhaskoro et al. [13] have tried to improve the model that suits Malaysian waxy crude oils, this model is yet to be made available in commercial applications for use by FA engineers. Additionally, it is worth noting that this paper also demonstrates that for Malaysian waxy crude oils, one cannot rely on modelling prediction alone without regression to measured viscosity data. Getting measured viscosity data sets at various conditions are still required. This test is not a tedious test, rather it can be done within hours and minimal sample volumes are required.

Further improvement on the wax viscosity model is required to describe Malaysian waxy crude oil non-Newtonian behaviors. Incorrect viscosity predictions will lead to difficulties when tuning the wax model and might lead to unphysical behaviors of the wax deposition. Additionally, to enable robust wax deposition modelling for field application, it is crucial to enable correct representation of each parameter that governs the wax deposition prediction in the pipelines.

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REFERENCES

[1] Zhang X, Pedrosa N, Speranza A, Queimada A, Richard S. (2019) Impact of fluid flow and thermodynamic wax models on multiphase wax deposition simulation. Paper presented at the BHR 19th International Conference on Multiphase Production Technology, Cannes, France, June 2019.
[2] Soedarmo AA, Daraboina N, Sarica C. (2017) Validation of wax deposition models with recent laboratory scale flow loop experimental data. Journal of Petroleum Science and Engineering, 149: 351-366. https://doi.org/10.1016/j.petrol.2016.10.017
[3] Singh A, Lee H, Singh P, Sarica C. (2011) Flow assurance: Validation of wax deposition models using field data from a subsea pipeline. Offshore Technology Conference. https://doi.org/10.4043/21641-ms
[4] Pedersen KM, Rønningsen HP. (2000) Effect of Precipitated Wax on Viscosity: A Model for Predicting Non-Newtonian Viscosity of Crude Oils. Energy & Fuels, 14(1): 43-51. https://doi.org/10.1021/ef9901185
[5] Matzain AB. (1999) Multiphase Flow Paraffin Deposition Modeling (Doctoral dissertation). University of Tulsa, Oklahoma.
[6] Giacchetta G, Marchetti B, Leporini M, Terenzi A, Dall'acqua DSV, Capece L, Grifoni, RC. (2017) Pipeline wax deposition modeling: A sensitivity study on two commercial software. Petroleum, 5(2): 206-213. https://doi.org/10.1016/j.petlm.2017.12.007
[7] Coronado O, Kak A. (2017) Workflow to Evaluate Wax Deposition Risk Along Subsea Production Systems. Offshore Technology Conference. https://doi.org/10.4043/27855-ms
[8] Sulaimon AA, Yusoff ME. (2015) Wax and Asphaltene Deposition Tendency of Malaysian Crude Oils. Proceedings of the International Conference on Integrated Petroleum Engineering and Geosciences. https://doi.org/10.1007/978-981-287-368-2_15
[9] Petrus TB, Azuraien J. (2014) Rheological Measurement of Waxy Crude Oil under Controlled Stress Rheometer: Determination of the Setting Parameters. Journal of Applied Sciences, 14(18): 2047-2053. https://doi.org/10.3923/jas.2014.2047.2053
[10] Anuar A, Rasib AA, Norpiah RM, Ali Z. (2022) Pigging the Unpiggable: A case study of waxy crude oil pigging simulation and field implementation. SPE Asia Pacific Oil & Gas Conference and Exhibition. https://doi.org/10.2118/210724-ms
[11] Vinay G, Wachs A, Agassant JF. (2006) Numerical simulation of weakly compressible

Bingham flows: The restart of pipeline flows of waxy crude oils. Journal of Non-Newtonian Fluid Mechanics, 136: 93-105. https://doi.org/10.1016/j.jnnfm.2006.03.003

[12] Bhaskoro PT. (2017) Viscosity prediction for waxy crude oil – Effects of physico-chemical parameters (Doctoral dissertation). Universiti Teknologi PETRONAS, Perak, Malaysia

[13] Bhaskoro PT, Japper@Jaafar A, Sariman MZ, Norpiah R, Shafian SR. (2020) Viscosity Model of Waxy Crude Oil Based on the Physico-Chemical Properties. Offshore Technology Conference Asia. https://doi.org/10.4043/30084-ms

[14] Barnes HA. (1997) Thixotropy - a review. Journal of Non-Newtonian Fluid Mechanics, 70 (1–2): 1-33. https://doi.org/10.1016/s0377-0257(97)00004-9

[15] Yoshimura A, Prud Homme RK. (1988) Wall slip corrections for couette and parallel disk viscometers. Journal of Rheology, 32(1): 53-67. https://doi.org/10.1122/1.549963

[16] Japper-Jaafar A, Bhaskoro P, Sean L, Sariman M, Nugroho H. (2015) Yield stress measurement of gelled waxy crude oil: Gap size requirement. Journal of Non-Newtonian Fluid Mechanics, 218: 71-82. https://doi.org/10.1016/j.jnnfm.2015.02.001

[17] PVTsim Nova Method Documentation

[18] OLGA Method Documentation

[19] Pedersen KS. (2003) Influence of Wax Inhibitors on Wax Appearance Temperature, Pour Point, and Viscosity of Waxy Crude Oils. Energy & Fuels, 17(1): 321-328. https://doi.org/10.1021/ef020142

[20] Santos IC, Oliveira P, Mansur CRE. (2017) Factors that affect crude oil viscosity and techniques to reduce it: A review. Brazilian Journal of Petroleum and Gas, 11(2): 115-130. https://doi.org/10.5419/bjpg2017-0010

[21] Wilke, C.R. and Chang, P. (1995) Correlation of Diffusion Coefficient in Dilute Solutions. AIChE Journal, 1(2):264-270.https://doi: 10.1002/AIC.690010222