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Experimental Analyses of Viscosity, Thermal Conductivity and Specific Heat Capacity of Waxy Crude Oil and a Computational Fluid Dynamics (CFD) Study

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Abstract

The rheological behavior of crude oil is highly dependent on wax/paraffin content, shear rate, and temperature. In this work, two types of paraffinic crude oils with different paraffin contents (7 and 25 wt.%), referred to as reference crude oils, were considered, and their viscosity, thermal conductivity, and specific heat capacity were measured at 22 and 26°C using Anton Paar MCR 302 rheometer and Flucon GmbH for thermal conductivity and specific heat capacity. The aforementioned measured values were then placed in a computational fluid dynamics (CFD) based model, and the results obtained for the dimensionless flow variables of the fully developed flow of the reference crude oils were successfully compared with the results obtained from other studies.

Keywords: *Computational fluid dynamics (CFD); Viscosity; Shear rate; Thermal conductivity; Specific heat capacity.*

1. Introduction

To compensate for decrease of velocity and pressure of waxy crude oil flow in a pipeline, under the conditions that it exhibits non-Newtonian behavior, engineers would have to optimize the transmission power, including transmission networks and heat exchangers. Knowing this objective requires correct predicting the rheological behavior, measuring the thermophysical properties, and estimating the distribution of velocity, pressure, and temperature of the fluid along the pipeline.

From a rheological point of view, fluids behave differently based on the stresses in which they resist [1-2]. Hence, they are classified into two groups of Newtonian and non-Newtonian fluids [3]. To describe the fluid rheological behavior, the equation of Power-law is typically suitable for modeling in the engineering calculations [4-6]. The petroleum industry is faced with the deviation of the fluid behavior from Newtonian to non-Newtonian because of the heat transfer phenomenon.

The study of flow variables, including velocity, pressure, and temperature based on a correct description of fluid rheological behavior, has received considerable attention from many researchers in this field. Many of these researchers have used the equation of Power-law for describing fluid rheological behavior, as mentioned earlier [4-6]. In these studies, in addition to the geometrical variety of flow paths (channel, pipe, and parallel plates), the variety of boundary conditions and environmental or laboratory conditions are considered.

Some researchers studied the heat transfer in a fully developed flow [7] of Power-law fluids, ignoring heat loss and viscosity variation caused by temperature changes, in order to provide a relation for the maximum dimensionless velocity on the centerline [8]. Also, the heat transfer was studied in a fully developed flow of a Power-law fluid in a pipe by ignoring heat loss, and the relation proposed for the linear distribution of shear stress on the pipe cross-section indicates a zero shear stress on the pipe centerline [9]. Besides, a no-slip condition on the pipe wall is considered. Furthermore, the rheological behavior and heat transfer of a Power-law fluid between parallel plates are studied. In this regard, the fully developed flow of Power-law

fluid between two parallel plates is studied in a certain range of flow behavior index [10]. Etemad *et al.* used the relationship between the Fanning friction factor [11] and Reynolds number [12-13] to estimate the pressure drop of the flow of Power-law fluid.

The temperature of the pipe wall and inlet were respectively assumed 22 and 26°C. In this work, two types of crude oils with different paraffin contents of 7 and 25 wt.% were studied, and their thermophysical properties, including viscosity, thermal conductivity, and specific heat capacity, were experimentally measured at 22 and 26°C.

Considering the shear stresses exerted on the reference crude oil flow in the pipe in the shear rate range of 100-600 s^{-1}, the results of rheometric tests indicate that the crude oils are non-Newtonian [14].

The physicochemical properties of the reference crude oils are presented in Table 1. According to the specifications of the reference crude oils, the difference between the pour points and the desired temperatures completely supports the assumption of no appearance of a solid phase at 22 and 26°C.

Table 1. Physicochemical properties of reference crude oils*

Reference crude oils	A	B
Density @ 26°C (g/cm^3)	0.872	0.896
API Gravity	38.50	22.30
Paraffin content (wt.%)	7	25
Sulfur content (wt.%)	0.41	4.25
Water content (vol.%)	<0.025	<0.05
Pour point (°C)	12	10
Nitrogen content (wt.%)	0.08	0.12

** More information is available upon request*

To calculate the distribution of velocity, pressure, and temperature of the crude oils along a pipeline, a numerical model based on Navier–Stokes equations and energy balance equation [15] was used, and results are successfully compared with results of other models.

2. Experimental

2.1. Materials

To study the influence of paraffin content, two types of crude oil with 7 wt.% and 25 wt.% paraffin contents, referred to as reference crude oils, were studied, as mentioned earlier. Any kind of crude oil with at least 5 wt. % paraffin content is referred to as paraffinic oil [16].

2.2. Apparatus

2.2.1. Viscosity

In this study, Anton Paar MCR 302 rheometer was used. MCR 302 provides two measuring methods, namely shear-rotary test, and oscillatory test. For each reference crude oil sample, a shear-rotary test was applied in this study. The shear rate profile, made up of different rotational speeds, was set to determine the shear rate. A detailed description of this equipment can be found elsewhere [14].

2.2.2. Thermal conductivity and Specific heat capacity

The Flucon GmbH measuring system facilitates the fast determination of thermal conductivity and specific heat capacity using the hot-wire method. The Flucon GmbH measuring system can operate in the stand-alone mode or by a Windows-based computer via a digital interface. A detailed description of this equipment is available elsewhere [14].

3. Numerical model

A detailed description of the numerical model is given elsewhere [15]. Briefly, the numerical model is based on Navier–Stokes equations and energy balance equation and benefits from the simultaneous capabilities of several models to calculate the flow variables. Considering

the dimensionless variables along with the dimensionless numbers (Reynolds, Brinkman, and Prandtl) and the parameters including the Power-law model indices, the pipe dimensions, and the thermophysical properties, the dimensionless output of the numerical model is defined.

Under specified dimensionless initial and boundary conditions, the dimensionless model is solved by Computational Fluid Dynamics (CFD) technique for each reference crude oil.

The finite-volume method is a standard CFD technique that is employed in the beginning to discretize the computational domain (solution field) and create a computational grid. Next, the general form of the dimensionless governing equations is considered. The main attraction of the finite-volume method is the explicit relation between the numerical algorithm and the general rule of physical conservation that facilitates the comprehension of the concepts for the user in comparison with other CFD techniques.

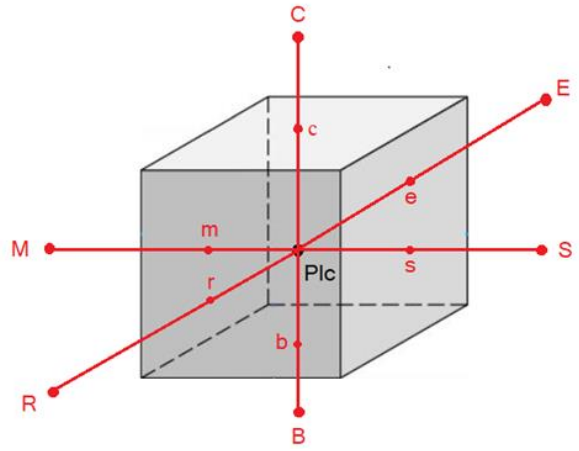

Figure 1. General three-dimensional CV and location of nodes neighboring general node

Moreover, integration of the governing equations on all control volumes (CVs) or meshes are a distinct feature of this particular method. Each CV contains a node at the center that preserves the flow data. Figure 1 shows a three-dimensional general CV with a general node Plc. In this figure, B, S, E, M, R, and C are the neighbors of the general node. The finite-volume method begins with the transfer of the computational or solution domain to a computational grid. The continuous computational domain must be discretized into several CVs provided that they do not interfere and fill the entire domain together.

Next, the terms of each integral equation obtained from partial differential equations are approximated over the general CV, discretizing the equations by substituting their terms with approximates. Given the dependence of the pressure and temperature on the velocity, it can be concluded that the velocity variable plays a key role in the approximation of the other two variables. Therefore, at first, the Semi-Implicit Method for Pressure-Linked (SIMPLE) algorithm was used to find the correct relation between pressure and velocity (pressure–velocity coupling algorithm). Accordingly, the pressure and velocity of the reference crude oil were estimated overall the general CV. By approximating the flow velocity on the general CV and inserting it into the discrete energy equation, the fluid temperature can be easily estimated on the CV. In the following, the approximations obtained on the general CV are expanded over the computational grid. This was carried out by solving the resulting system of algebraic equations by line-by-line or Tri-Diagonal Matrix Algorithm (TDMA) method. An attractive feature of the finite-volume method is that the results, including the unknown variables, apply to all CVs and, therefore, the entire computational domain.

On the other hand, the following was taken into account when discretizing the computational domain.

- The accuracy of a numerical method depends on the number of CVs in the grid. More CVs lead to higher accuracy of calculations. However, computational cost and time increase in proportion to the rise in the number of CVs.
- When establishing a computational grid, first, the faces of CVs must be determined; then, the nodes must be placed at the centers of CVs.
- Consider the steep velocity and temperature gradients near the inner surface of the wall compared to other regions, smaller CVs and closer nodes are assumed (Figure 2).
- The faces of CVs take place at the boundaries of the computational grid and not the nodes.

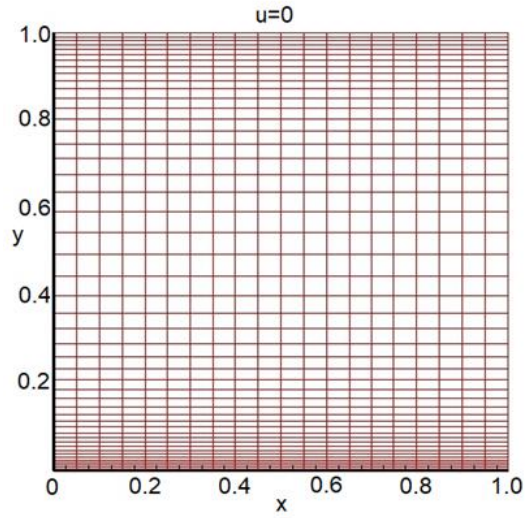

Figure 2. Computational domain discretization

The next step in the finite-volume method following the discretization of the computational domain is discretizing every term of integral equations obtained from the integration of partial differential equations in the numerical model on the computational grid. Accordingly, to present a unified method, the general form of the equations is presented before integration.

By integrating the general equation and discretizing its terms, a suitable algorithm is obtained for discretizing the dimensionless equations governing the problem in the computational grid. Another step in the CFD technique is to solve the system of algebraic equations obtained by discretizing the equations., which was carried out by iterative TDMA method due to complexity. Accordingly, the velocity and pressure of the Power-law crude oil flow were calculated for all Control Volumes (CVs) throughout the grid using dimensionless continuity and momentum equations. On the other hand, the flow velocity and pressure were coupled in dimensionless equations. Therefore, before taking the TDMA approach, the SIMPLE algorithm was used to obtain the correct correlation between flow velocity and pressure (pressure–velocity coupling algorithm).

The calculation of the temperature is not as complicated as calculating the velocity and pressure. Calculating the temperature for each of the reference crude oils using the energy equation is contingent upon knowing the velocity in any CV of fluid. By substituting the estimated velocity in the equation, the temperature of the fluid is also determined in any CV of the computational grid. In the case of computing the pressure and velocity on the general CV, the subject is slightly different. The momentum and continuity equations have complicated combinations for all velocity components that appear in the continuity equation in addition to momentum equations. The pressure and velocity are coupled in the momentum equations, and no separate equation is available for obtaining the pressure. If the pressure gradient is known, the velocities can be obtained from the momentum equations without any difficulty. However, often that is not the case in reality. The SIMPLE algorithm starts with an initial guess of the velocity and pressure. The guess is then used to solve the momentum equations. If the speculated pressure is correct, the velocities should satisfy the continuity equation. Otherwise, the pressure and velocity will be corrected, drawing on a special formulation that is readily presented, replacing the results with the initial guess, and solving the equations again. The process iterates until the results satisfy the continuity equation. This algorithm requires storage to be set for the velocities, which can be done by using non-collocated grids.

4. Results and discussion

4.1. Viscosity measurement

The experimental results (Table 2) and viscosity-shear rate curves (Figures (1-a) and (1-b)) were generated using the aforementioned equipment. As Figure (1-a) shows, by increasing the shear rate, the viscosity of reference crude oil B decreases, and the shear rate variation does not have a meaningful effect on the viscosity of reference crude oil A at 26°C. As shown in Table 2, at 26°C, the viscosity of reference crude oil B changes from 0.410 to 0.123 Pa.s with changing the shear rate, while the viscosity of reference crude oil A approximately remains unchanged at 0.091 Pa.s. In other words, the viscosity of reference crude oil A is independent of the shear rate, and thus the rheological behavior of fluid does not depend on the shear rate. As shown in Figure (1-b), the reference crude oil with the higher paraffin content has a higher viscosity at 22°C. The viscosity is directly related to the amount of paraffin

crystallized at this temperature. Meanwhile, the slope curve becomes upward; therefore, the viscosity reduces sharply and tends to a constant value by increasing the shear rate.

Table 2. Experimental viscosity-shear rate data at 22 and 26°C

Shear rate (s^{-1})	Viscosity (Pa.s)			
	A		B	
	26°C	22°C	26°C	22°C
100	0.091	0.098	0.410	0.525
120	0.091	0.098	0.343	0.462
140	0.091	0.098	0.292	0.401
170	0.091	0.098	0.257	0.342
200	0.091	0.098	0.228	0.291
250	0.091	0.098	0.202	0.246
300	0.091	0.098	0.182	0.201
380	0.091	0.098	0.160	0.168
450	0.091	0.098	0.141	0.149
600	0.091	0.098	0.123	0.127

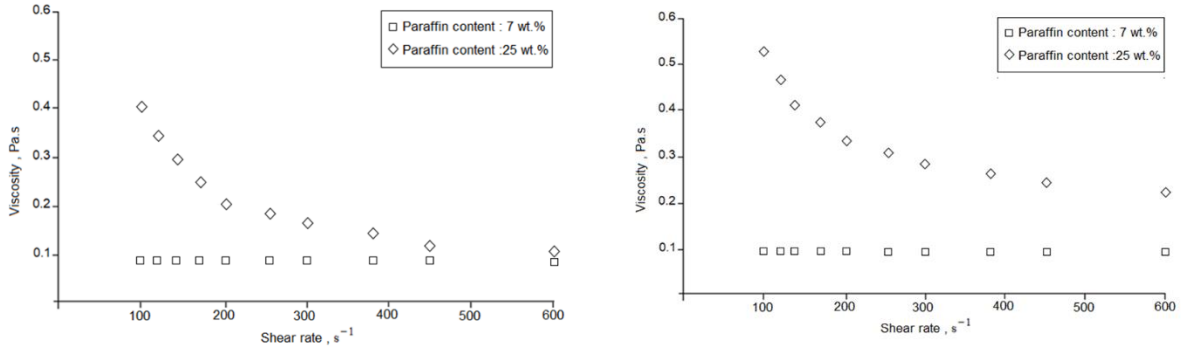

Figure 3. Viscosity-shear rate curves for reference crude oils (a) at 26°C (left) (b) at 22°C (right)

As it is observed, by decreasing the paraffin content, the slope of the curve falls, so that for the reference crude oil A, changes in the curve are close to zero, and the curve is almost a horizontal line. In other words, changes in the shear rate at 22°C do not have much effect on the viscosity of this fluid, and thus the rheological behavior of fluid does not depend on the shear rate.

As shown in Table 2, if the temperature reduces from 26°C to 22°C, the maximum viscosity of reference crude oils B and A increases from 0.410 to 0.525 Pa.s and from 0.091 to 0.098 Pa.s, respectively. At higher paraffin content, the temperature fall causes the formation of more paraffin crystals and a stronger internal structure in reference crude oil B. Accordingly, the increase in viscosity rate of reference crude oil B is higher than reference crude oil A.

4.2. Thermal conductivity and specific heat capacity measurements

According to the results in Table 3, when the temperature changes from 26°C to 22°C, the thermal conductivity and specific heat capacity for each of the reference crude oils change with a precision of about 0.001 and 0.01, respectively. These parameters have no significant sensitivity to the temperature changes from 26°C to 22°C.

Table 3. Thermal conductivity and specific heat capacity data at temperatures of 26°C and 22°C

Reference crude oil	Temperature (°C)	Thermal conductivity (J/g °C)	Specific heat capacity (W/m °C)
A	26	1.831	0.138
	22	1.829	0.139
B	26	1.901	0.144
	22	1.898	0.145

4.3. Numerical model results

Taking into account a pipe specification including the pipe diameter = 21 cm and the pipe length = 300 cm, the measured values of viscosity, thermal conductivity, and specific heat capacity for the reference crude oils were placed in the numerical model (ignoring heat loss) and the results obtained for the dimensionless flow variables including the velocity, pressure, and temperature of the fully developed flow of the reference crude oils A and B were compared with the results obtained from other studies. Table 4 indicates the nearly identical results for the dimensionless maximum velocity with a maximum deviation of ±0.0.3, for the dimensionless temperature with a maximum deviation of ±0.0.4, and for the dimensionless pressure drop with a maximum deviation of ±0.05, respectively.

Table 4. Comparison of dimensionless flow variables of reference crude oils obtained from this study and those obtained from the literature

Maximum dimensionless velocity on the centerline						
Reference crude oil	This study				Skelland [8]	
A	1.48				1.5	
B	1.33				1.3	
Dimensionless temperature on the centerline						
Reference crude oil	This study				Chhabra *et al.* [9]	
A	0.27				0.24	
B	0.66				0.62	
Dimensionless pressure drop of reference crude oil B in the vicinity of wall/plate inner surface						
	x					
	0.05	0.25	0.5	0.7	0.8	0.9
This study	0.26	0.27	0.07	0.03	0.01	0.01
Etemad *et al.* [10]	0.24	0.22	0.09	0.05	0.03	0.02

5. Conclusion

Two reference crude oils with 7 and 25 wt.% paraffin contents were studied, and the viscosity-shear rate curves were reported by performing the shear-rotary tests in the shear rate range of 100-600 s^{-1} at 26 and 22°C, and changes in the curves were investigated. The viscosity of reference crude oil B significantly decreases with increasing the shear rate. However, the shear rate does not significantly change the viscosity of crude oil A. The thermal conductivity and specific heat capacity of the reference crude oils are not significantly sensitive to temperature variations from 26 to 22°C.

Using the above-mentioned measured values and the CFD-based model, nearly identical results for the dimensionless maximum velocity, the dimensionless temperature, and the dimensionless pressure drop were obtained in comparison with three previously reported models.

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