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Rheological and Computational Analysis of Crude Oil Transportation

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***Abstract*—**Transportation of unrefined crude oil from the production unit to a refinery or large storage area by a pipeline is difficult due to the different properties of crude in various areas. Thus, the design of a crude oil pipeline is a very complex and time consuming process, when considering all the various parameters. There were three very important parameters that play a significant role in the transportation and processing pipeline design; these are: viscosity profile, temperature profile and the velocity profile of waxy crude oil through the crude oil pipeline. Knowledge of the Rheological computational technique is required for better understanding the flow behavior and predicting the flow profile in a crude oil pipeline. From these profile parameters, the material and the emulsion that is best suited for crude oil transportation can be predicted. Rheological computational fluid dynamic technique is a fast method used for designing flow profile in a crude oil pipeline with the help of computational fluid dynamics and rheological modeling. With this technique, the effect of fluid properties including shear rate range with temperature variation, degree of viscosity, elastic modulus and viscous modulus was evaluated under different conditions in a transport pipeline. In this paper, two crude oil samples was used, as well as a prepared emulsion with natural and synthetic additives, at different concentrations ranging from 1,000 ppm to 3,000 ppm. The rheological properties was then evaluated at a temperature range of 25 to 60 °C and which additive was best suited for transportation of crude oil is determined. Commercial computational fluid dynamics (CFD) has been used to generate the flow, velocity and viscosity profile of the emulsions for flow behavior analysis in crude oil transportation pipeline. This rheological CFD design can be further applied in developing designs of pipeline in the future.

***Keywords*—**Natural surfactant, crude oil, rheology, CFD, viscosity.

I. Introduction

THE Rheological CFD technique has become an industrial simulation tool for engineering and research area, which includes flow behavior, pipeline design, and performance and analysis. Advances in technology have enormously increased the speed of the processor resulting easy accessibility of computational simulations at low cost. Crude oil is a complex mixture of paraffin, aromatics, naphthenes, resins and asphaltenes and their transportation by pipeline from production areas to refinery is the general process in the petroleum industry. The component mixture of crude oil depends upon the temperature and composition of the system. Crude oil transportation through pipelines in cold regions results in deposits of waxy material in the inner wall of pipelines. This causes a decrease in the hydraulic diameter of the pipeline which decreases the flow rate and the efficiency of the pump, and in the worst case, blockage of the pipeline [1]. Meanwhile, the heating of the transportation pipeline to decrease the viscosity of crude oil is quite complicated process [2]. The rheological properties of crude oil were fundamental for crude oil pipeline design and operation [3]. Knowledge of rheological properties is vital role for the petroleum industry. Viscosity, at different shear rates and the shear stress of crude oil were very important in the petroleum field. The fluid behavior can be categorized as Newtonian and non-Newtonian (pseudoplastic, Bingham plastic, Bingham and Dilatant), and surfactants were used to change fluid behavior in the pipeline. In this investigation, a detailed analysis of the flow behavior of crude oil through a horizontal pipeline is simulated by using ANSYS 15.0 and the rheological behaviour was assessed with a RheolabQC rheometer.

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II. Experimental Work

A. Rheological Technique

In this investigation, a crude oil sample was collected from the Indian Oil corporation refinery Panipat, Haryana and a natural surfactant i.e. rice grain surfactant was collected from a Patiala distillery. The advantage of using rice grain surfactant was that it was very easy to extract and can be prepared in required quantity. A measured volume of crude was placed in a container and stirred using a magnetic stirrer at 1,000 rpm for 1.5 hours to ensure a proper stable homogeneous mixture with natural surfactant at a concentration of 1,000 ppm to 3,000 ppm. The rheological behavior includes steady and viscoelastic characteristics, which were investigated using a RheolabQC made by the Anton Paar Company Ltd, Germany. The rheological parameters of the heavy crude oil were evaluated by measuring the shear stress at the specific shear rate 0.8 -500 S^{-1}. It was found that a small proportion of the drag reducing agents reduce the viscosity of the crude oil suspension.

B. Computational Model Development

Fig. 1 shows a model of transportation pipeline which was generated by solid work in 2012. The model consists of three sections: crude oil inlet, surfactant inlet and the outlet of the pipe. A detailed geometry of the pipeline was shown in Table I.

TABLE I
DESCRIPTION OF PIPELINE GEOMETRY

Description	Value	Unit
Pipe inner diameter	0.025	m
Pipe length	1	m
Crude oil inlet velocity	0.01	m/s
Crude oil density	870	kg/m^3
Crude oil viscosity	0.051	kg/m-s

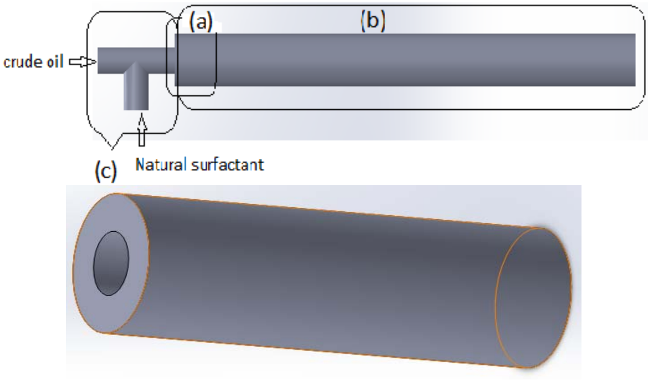


Fig. 1 Model of the pipe flow configuration with the elbow being considered for analysis

C. Meshed Geometry with Flow Direction

Crude oil and natural surfactant is supplied to the pipeline, as represented in Fig. 1, where sudden expansion is represented by (a), the straight section is represented by (b) and the Tee section represented by (c) in the geometric pipeline. The meshing of the pipeline geometry was done with the help of ANSYS R15.0FLUENT code, as shown in Fig. 2.

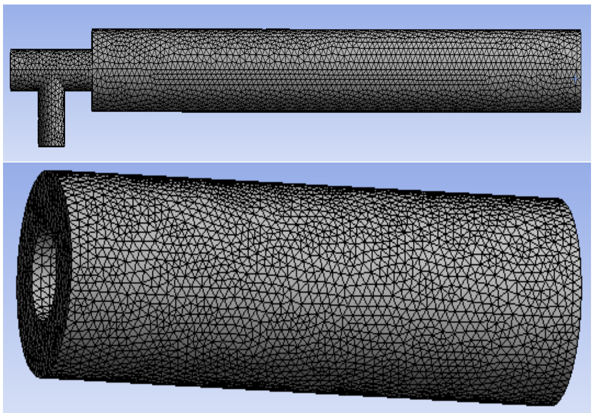


Fig. 2 Tetrahedral mesh adopted in the CFD analysis

TABLE II
MESH QUALITY PARAMETER

S.NO.	Name of geometry	Cell Size	Mesh Size	Mesh Type
1	Tee with straight pipe line	5mm	174234	Tetrahedral Elements
2	Straight Pipe	5mm	107646	Tetrahedral Elements

Table II represents a grid independency test that was carried out for both models and the optimum mesh size was obtained as 174234 and 107646, respectively. Tetrahedral mesh geometry was selected for accounting the velocity effect more accurately.

D. Boundary Conditions

In this investigation, the flow has been initialized by filling a pipe with crude oil from the inlet with a specific impulse velocity. Surfactant was then introduced in the pipe through other section.

Pressure based segregated solver with implicit formulation was selected. The Volume of Fluid (VOF) model and Explicit Volume of fluid scheme was selected to solve the unsteady flow in the pipeline. Test fluids were defined using material data base of ANSYS and the properties were changed according to the current research. The operating pressure was set as atmospheric pressure (default setting), and gravity is considered in Z-direction as -9.81 m/s^2.

The inlet velocities of both the fluids were assumed to be uniform and specified as follows:

- At x = 0, y = 0; U x= U oil and U y = 0 (m/s).
- At x = 0.25 m and y = -0.300 m; U y = U surfactant and U x = 0 (m/s).

The wall was assumed to be stationary and a no slip condition was imposed. Pressure outlet boundary was selected and the diffusion flux variables at the exit were taken as zero. Time step size used in all simulations was 0.001 s.

III. RESULTS AND DISCUSSION

A. Steady Flow Behavior

The flow behavior of high sulfur and low sulfur crude oil was investigated in terms of viscosity-shear rate using the CR mode of the RheolabQC. Figs. 3 and 4 show the complex flow behavior for the measured results at different temperatures. It was observed from Figs. 3 and 4 that the crude oil exhibits non-Newtonian shear thinning behavior over the examined range of shear rates 0-500 S^{-1}, in which the viscosity decreases with temperature when it was heated from 35°C to 45°C. As the shear rate increases, the chain type molecules disentangled, stretched and reoriented parallel to the driving force, and hence, reduced the heavy crude oil viscosity [4], [5]. It was also demonstrated that the viscosity differences were larger at low shear rates than at high shear rates. As the temperature increases, the components of the higher molecular weight of the heavy crude oil, such as asphaltenes, do not have the chance to agglomerate and form large chain molecules, and it affects the carbon-carbon bond between the solid particles, eventually reducing the oil viscosity. From viscosity versus shear rate curve, it was found that there was a certain viscosity reduction over the tested temperatures. This can be attributed to the strong effect of temperature on the viscosity and chemical structure of heavy components of the crude oil such as wax andasphaltene [6], resins and waxes.

The viscosity of crude oil at 35°C and 45°C was found as 0.0063 Pa-s, 0.0044 Pa-s. On addition of the surfactant, the viscosity of high sulfur crude oil at 35°C was around 0.0050 Pa-s. In a comparison of both results, viscosity on addition of the surfactant drops by 0.001 Pa-s and at 45°C was around

0.0032 Pa-s. The reason for developing a crude-surfactant mixture was to form a less viscous and dense crude oil that will be more desirable and suitable for the pipeline transportation. In the CS mode, shear stress was applied to a test sample by means of extremely low inertia [7]. Figs. 5 and 6 show the viscosity flow behavior of the high sulfur and low sulfur crude oil when it was mixed with 2,000 ppm and 1,000 ppm of the surfactant of rice grain, respectively. The viscosity flow behavior of the crude-surfactant mixture reports much less viscosity than that observed for the high sulfur and low sulfur crude oil.

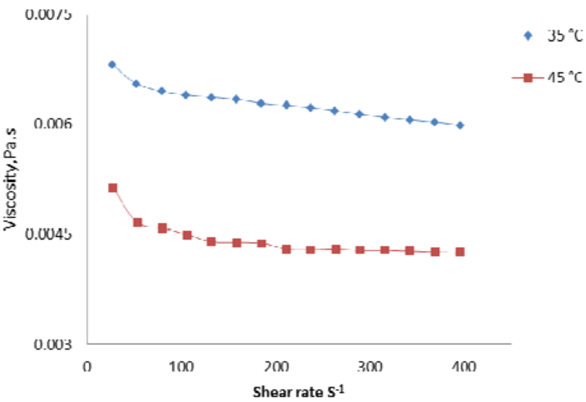


Fig. 3 Viscosity profile of high sulfur crude oil at different temperatures

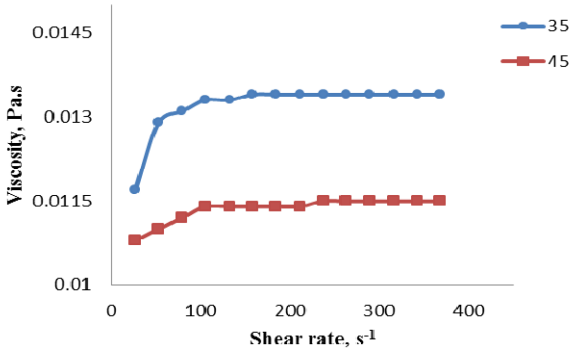


Fig. 4 Viscosity profile of low sulfur crude oil at different temperatures

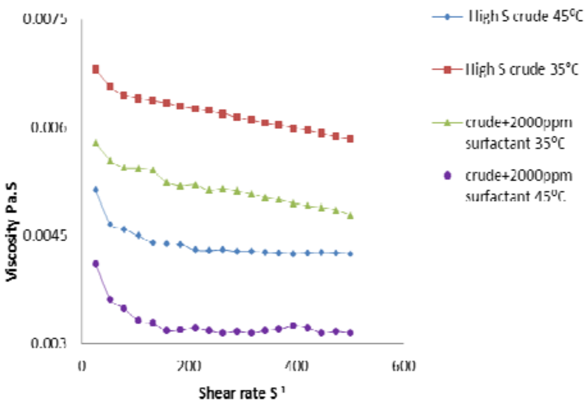


Fig. 5 Comparison between high sulfur crude oil samples and 2,000 ppm of rice surfactant at different temperatures

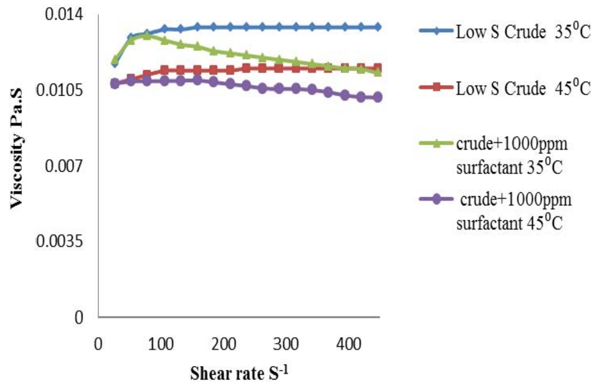


Fig. 6 Comparison between high sulfur crude oil samples and 2,000 ppm of surfactant at different temperatures

B. Transport Profile in Crude Oil Pipeline

The velocity vector and stream in the pipeline flow was analyzed by ANSYS 15.0 software. The velocity vector and stream line were generated as shown in Fig. 7.

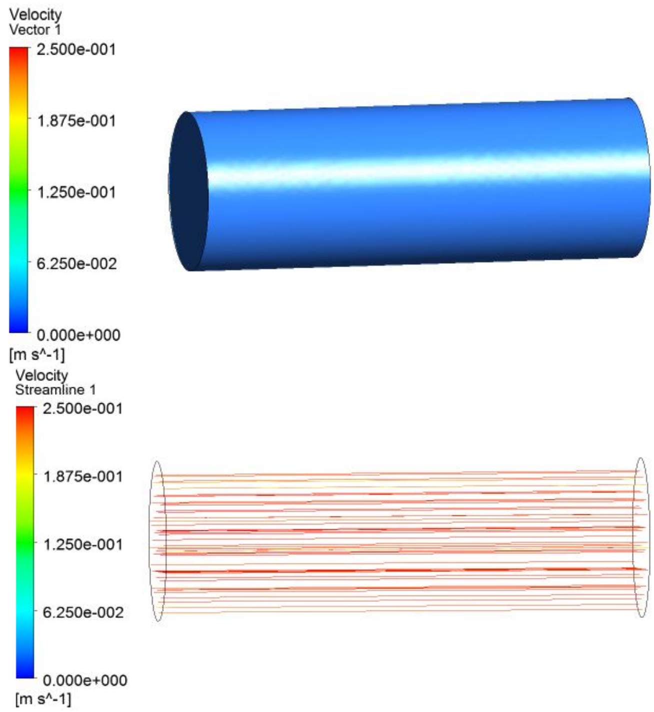


Fig. 7 Velocity vector and stream line of pipeline flow

C. Velocity Profile

Radial distribution of velocity for wavy and annular flow was shown in Fig. 8. In stratified wavy flow, oil phase has laminar and surfactant has turbulent flow. Hence, the mixture velocity was high for surfactant and low for oil phase. In annular flow, the velocity profile looks like a parabola showing maximum velocity at the center (which was occupied by oil phase), as shown in Fig. 8.

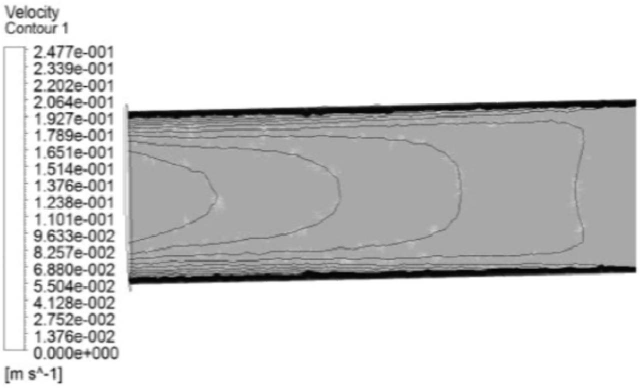
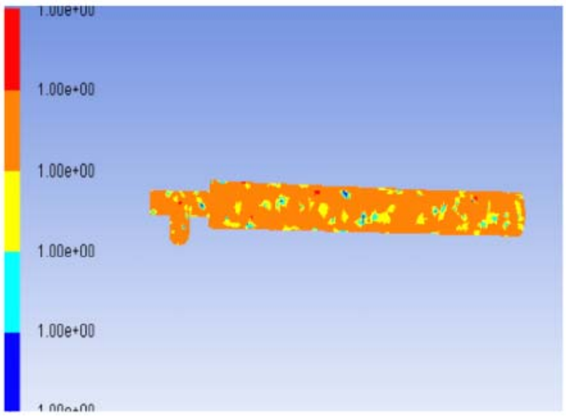
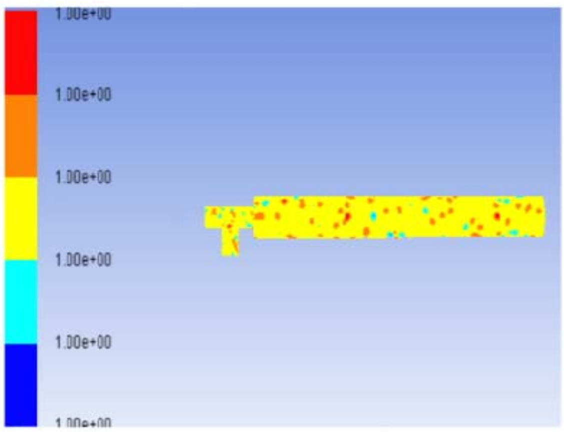


Fig. 8 Velocity contour of pipeline flow at velocity



(a)



(b)

Fig. 9 Particle concentration of different oil and natural surfactant at velocities (a) $U_{surfactant}$=0.1, U_{Oil}=0.13, and (b) $U_{surfactant}$ 0.24 and U_{Oil}=0.13

D. Particle Tracking in the Model

Particle tracking can be performed using fluorescent or optical labels; however, it was more costly than ANSYS Particle tracking, thus CFD provide particle tracking at a faster and cheaper rate. The practical use of CFD modeling as a design tool was limited by the accuracy of the flow models and particle-tracking procedure. Particle tracking was the observation of the flow of each particle within crude oil. The trajectory can be analyzed to identify modes of motion such as obstacles or regions of fast transport (e.g. due to active transport or flow). Fig. 9 shows the particle concentration of different phases.

IV. Conclusion

Rheological CFD design allows economic analysis of crude oil transportation pipeline flow.

The high sulfur crude oil shows the non-Newtonian shear thinning characteristics. As the temperature increases the viscosity of crude oil decreases and shows Newtonian flow behavior at 45°C.

The addition of rice grain as an additive in heavy crude oil suspension can be useful for the design of pipeline of oil transportation system.

Rheological and computational analysis can be helpful for a crude oil transportation pipeline, as well as the process pipeline of a refinery.

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