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START-UP FLOW VISUALIZATION OF THIXOTROPIC MATERIAL IN THE HORIZONTAL PIPES GEOMETRIES USING PARTICLE IMAGE VELOCIMETRY

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Abstract
In oil production in ultra-deep water fields, difficulties can appear in the transport of oils with high paraffin content. During shut down situations of the crude transportation caused by emergency or maintenance activities, the crude oil in rest shows a gel-like structure, usually exhibiting a thixotropic yield-stress behavior after a period of time. In order to restart the flow, high pressures are applied which can cause risks of damage to the transporting pipeline network and can compromise the operation. As a measure to prevent these risks, the dimensions of the pipeline are overestimated, which is reflected in high operating costs that sometimes make projects unviable. Therefore, an accurate prediction of the minimum pressure to restart the flow is necessary as an operational requirement. The objective of this experimental study is to investigate and visualize the start-up flow of yield stress materials in smooth and grooved pipelines. The velocity profiles, the presence of plug structure and the solid-fluid transition are analyzed before and during the yielding of the fluid. For a better understanding of the flow dynamics of these materials, a test section of length 0.980 m with a circular cross-section of inner radius 0.011 m was attached to two reservoirs to control the inlet and outlet pressure. A 2D-Particle Imaging Velocimetry system is used as visualization setup. An aqueous Laponite® solution of 2 wt% is used as thixotropic material, in order to verify the start-up flow constant pressure values were applied for a period 600 seconds, and pressure measurements were obtained by pressure transducers located at the inlet and outlet of the test section. A relationship between the minimum start-up flow pressure drop and velocity field evolution was depicted. Also, the time required to restart the flow depends mainly on the applied pressure and the viscosity that decreases with time. Finally, it was observed that a slip velocity is presented during the restart-up flow, which can be scaled as a power-law relation with the shear stress at the wall and the wall velocity gradient.

Keywords
Thixotropic material; yield stress; start-up flow; wall slip.

Introduction

The production of paraffinic oil in offshore fields, especially in ultra-deep water is affected by problems of blockage of the transporting lines, normally caused by the growth of paraffin crystals due to the decrease of the temperature below the Wax Appearance Temperature (WAT). With the continual appearance of paraffin crystals, the rheological properties of the oil become complex which can result in a gel-like structure ([1], [2]). Under such condition, restarting the flow may present some risks, as the pumping system needs to provide the pressure necessary to break the gel structure and restart the flow, known as start-up pressure, in general, this pressure is higher than the operational one due to the yield stress of the fluid.

Chala *et al*. studied the transport of waxy oil in offshore fields and previous research on the behavior of waxy oil in Newtonian and non-Newtonian regions ([2]). In addition, the restart-up process and the associated problems encountered, flow assurance and management of waxy crude oil, flow improvers of waxy crude oil gel following sufficient cooling were thoroughly discussed. They concluded that the rheological behavior of the final gelled oil is crucial for the determination of the restart pressure, as also the yield stress, elasticity and the thixotropy effects.

Chen *et al.* [3] studied the use of differential scanning calorimeter to attempt to establish the amount of wax in waxy crude oil. The investigation led to the formulation of an equation that allowed predicting wax precipitation, and thus using it to solve the precipitation problem. In a similar study Carnahan *et al.* ([4]) used Ronningsen observations regarding pour point temperature, and then indicated that it was possible to predict the amount of wax in the gelled crude oil assuming zero waxes in WAT.

A non-zero yield is observed for waxy crude oil after rest time [5]. According to Hou *et al.* ([6]), four factors that affect the yield strength of waxy crude oil were identified based on the laboratory test performed: temperature history, shear history, aging and compositions. It was also found that at higher wax content, the yield stress increases exponentially. In a study that evaluated the influence of temperature, when other parameters were kept constant, Jemmett *et al.* ([7]) observed a linear relationship between gel strength and temperature.

In addition to exhibiting non-zero yield, waxy crude oil also exhibits thixotropic behavior, that is, time dependent change of viscosity of a waxy crude oil in non-Newtonian region [8]. The effects of thixotropic behavior on flow restart are investigated using a stress-controlled rheometer in Mortazavi *et al.* ([9]). The authors conclude that the thixotropic effects to be getting higher when the crude oil was at lower temperatures. The thixotropic behavior made the viscosity of the gel to be time and shear history dependent, displaying a shear-thinning behavior.

In this work, the start-up flow is studied in a straight pipe configuration. Constant pressure values were imposed on the two thixotropic solutions and subsequently displacing it and causing it to yield. We measured the pressure in the Laponite® solutions and using the particle image velocimetry (PIV), the transient flow field of the fluid was studied. The presence of wall slip is observed and reveals that it is a phenomenon present in the start-up thixotropic flow, which increases with the shear stress on the wall.

Methodology

Rheological testes

To perform the flow curve tests, the HR-3 rotational rheometer (TA Instruments) was used. The rheological tests were carried out at a temperature of 22 ºC, in order to represent the same conditions defined in the laboratory. To obtain the data of shear stress by shear rate, the implemented procedure consisted in the application of constant shear rate, from 10 to 4000 s^{-1} for the aqueous Laponite® solution (2wt%). Two different geometries were used to carry out the tests: grooved Couette geometry (GC-G) and smooth Couette geometry (SC-G), when GC-G is used for low shear rate range and the SC-G in the intermediate and high shear rate range. The flow curve is then constructed with the steady-state shear stress values obtained in the constant shear rate tests

Experimental Setup

An experimental setup was designed to study the start-up flow of Laponite® solution (2wt%). Figure 1 shows a schematic illustration that identifies the main components and the subcomponents of the experimental setup. The device is basically made up of two systems: hydraulic and control/acquisition. The hydraulic system is integrated into three parts: the main pipe (item C), two auxiliary sections (item B), and two reservoir tanks (item A). These tanks were identified the external tank and the internal tank. Therefore, the tank placed before the test section (right) was named the external reservoir tank (or external reservoir), and the opposite side (left) internal reservoir tank (or internal reservoir). Both tanks had a quick coupler adapter on the top cap for filling with compressed air, and also had manometer type Bourdon (Item K) with 0 to 1.6 bar operating range, a pressure relief valve (Item J. Finally, to visualize the changes in the tanks' level due to the start-up of fluid, a level sight glass was installed (Item H). To record the pressure difference during the flow restart, two pressure sensors (Item D) were used. These pressure sensors operate between a range of 0 to 0.6 bar and guarantees precision measurements with a maximum measuring deviation of as low as 0.05% of span. Temperature monitoring is done by four thermocouples (type J) (Item F) with an operating range from -50 oC to 150 oC externally attached to the acrylic tube by clamps.

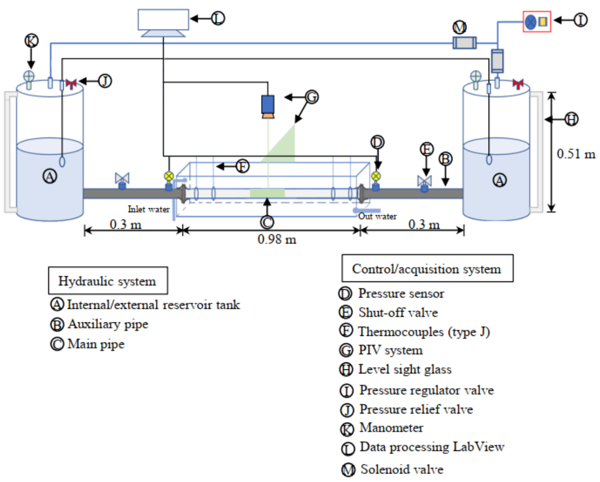

Figure 1. Schematic illustration of the components of the experimental setup

The pressurization system consisting of a pressure regulator valve and a manometer model with operating range 0 to 1.6 bar (Item I), and two solenoid valves (Item M) were connected to the compressed air system of the LabFlow of CERNN's allowed to impose the pressure required for start-up flow during the tests. The pressure values imposed were controlled through a program developed in LabVIEW, which allowed that the set pressure values to be applied with greater precision.

The visualization of thixotropic flow through the experimental setup is possible using a particle imaging velocimetry (PIV) technique. In this study, spherical glass tracer particles with a diameter of 10 µm were used to visualize the flow. The particles absorb light at a wavelength of 532 nm and emit it back at 532 nm. Figure 2 shows the setup for using the PIV, a laser system of 60 mJ is synchronized with a CMOS camera by a synchronization box. A visualization plane is obtained after setting the camera at 90 degrees with the laser beam.

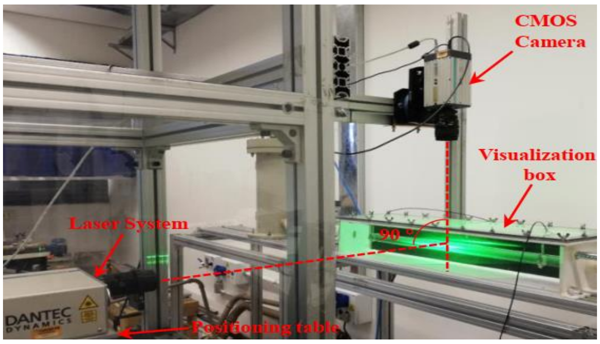

Figure 2. Visualization system setup. The plane of the laser beam and the visualization plane of the camera is set in a perpendicular configuration.

Experimental procedure to analyze the transient starting flow under constant pressure application

The start-up flow is a process that involves the temporal evolution of the flow fields when an external force is applied. In order to evaluate this transient response for the thixotropic fluid as a function of pressure drop (wall shear stress), experimental tests were performed under the temperature conditions of 22 ºC following the protocol described below:

1. Set the required pressure.
2. Start recording of pressure measurements and recording of flow images using the PIV technique 10 s before imposing pressure up to t equal to the set value of wall shear stress.
3. The pressure regulating valve opens
4. At t=300 s, record images using the PIV technique
5. At t=600 s, record images using the PIV technique.
6. Finish recording of data, after t=600s.
7. Finally, close the pressure regulator valve

Velocity vector field measurements and flow patterns obtained by PIV technique

To obtain the mean velocity vector field, it was first necessary to acquire images showing the displacement of the seeded particles in the fluid. This image recording process was performed using the experimental setup shown in Fig. (3).

Initially in Fig. (3), the displacement of the tracer particles is detected, and after, using the *dewarping* function, the data is smoothed to reduce the effects of refraction. Then, a correlation is performed, next a correlation plane is formed, and the particle displacement as a vector is generated. Through the detection of *outliers*, the vectors that are out of trend are eliminated. Finally, the vector statistic function allows us to obtain a velocity vector field.

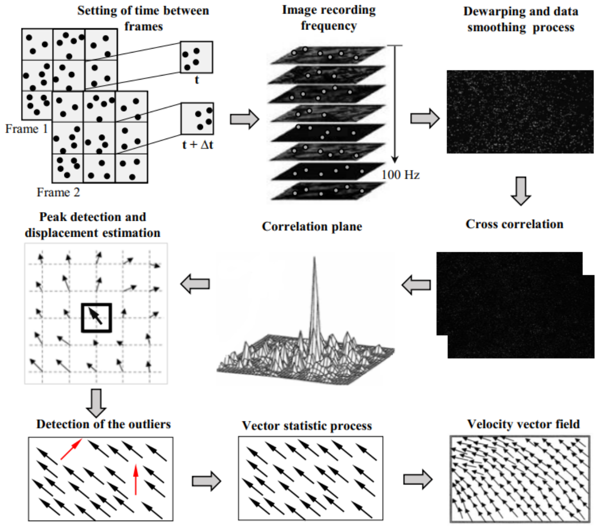

Figure 3. Process for image acquisition and post-processing steps with *Dynamic Studio*® software

Results and Discussion

Rheological measurements

Figure 4 and 5 show the results for the shear stress data obtained for high, intermediate and low shear rates, respectively. It is possible to observe in Fig. (5) that, for low shear rate values, in the first instants for the rates of 0.1 and 0.01 s^{-1}, the behavior contrasts with that observed for the rate of 1 s^{-1} and greater than 1s^{-1}. This behavior may be related to destructuring and structuring processes, that is, the gel-like structure does not completely break. On the other hand, in Fig. (4) the stress attains a minimum and then evolves to a higher steady-state value.

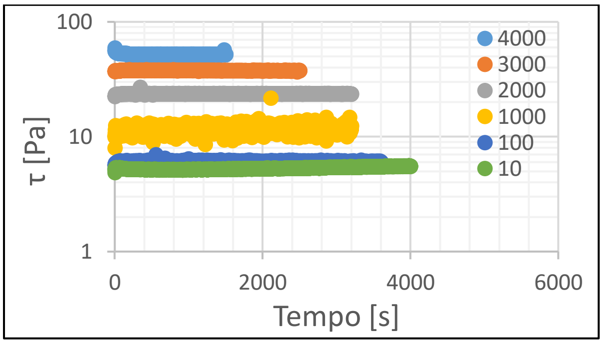

Figure 4. Constant shear rate tests for the Laponite suspension. Intermediate and high shear rates

This behavior indicates that, for each shear rate, the initial structuring level in these tests is lower than the one corresponding to steady state, probably due to microstructure breakdown during loading the sample into the rheometer. Therefore, the microstructure builds up during the test, as opposed to what occurs in the higher shear rate tests shown in Fig. (4), where the microstructure breaks down, and hence the stress decreases monotonically towards the steady-state value.

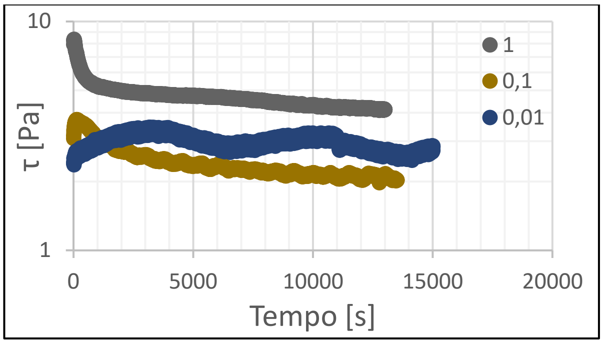

Figure 5. Constant shear rate tests for the Laponite suspension. Low shear rates

Figure 6 shows the flow curve for the thixotropic fluid. The results show that a low rate seem to appears a shear banding effect, since the points within the shear rate range are not uniform. According to Divoux *et al.* ([11]) the slope in the region ($\dot{\gamma}$ ≤ 1 s^{-1}) is negative, and the cause is related to the non-shearing of the sample in this region. Therefore, if instead of imposing a shear rate, if he had imposed a shear stress, the negative-slope portion would not have been reached.

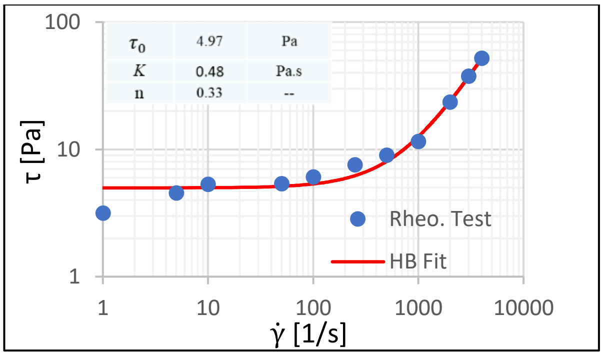

Figure 6. **F**low curve of the Laponite suspension.

The fit show in Fig. (6) was obtained considering that $\dot{\gamma}$≥1 s^{-1} and the Herschel-Bulkley equation given by Eq. (1). The values of the parameters are given in Fig. (6).

$$\tau_y = \tau_0 + k\left(\dot{\gamma}_y\right)^n \qquad \tau_y \geq \tau_0$$
$$\dot{\gamma}_y = 0\,, \tau_y \leq \tau_0 \qquad (1)$$

Figures 7 and 8 show that initially the fluid is at rest and fully structured. Then, when the stress exceeds the yield stress, a quick microstructure breakdown is observed, and then the viscosity begins to decrease. However, it is possible to observe that a several units of time are necessary before the collapse of the microstructure occurs, perhaps because the viscosity is still very high. The sudden collapse of the microstructure can be associated with the avalanche effect reported by [12].

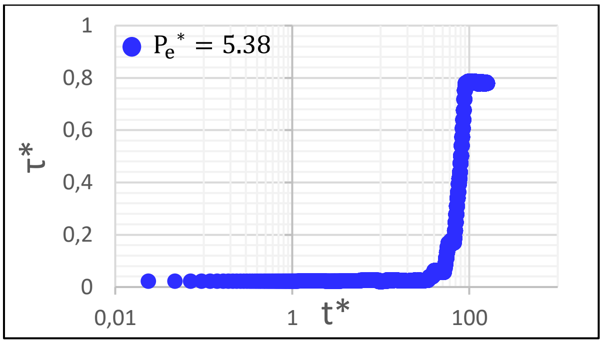

Figure 7. Dimensionless time evolution of dimensionless shear stress for a dimensionless entrance pressure rates in smooth pipe.

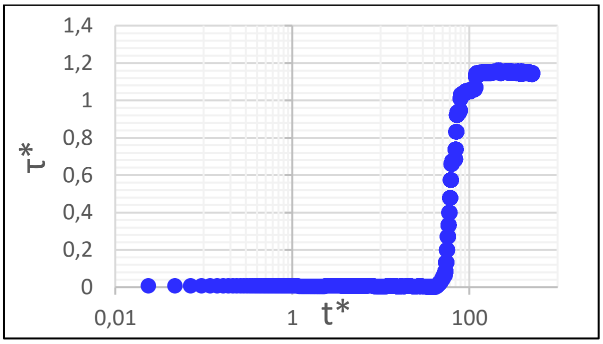

Figure 8. Dimensionless time evolution of dimensionless shear stress for a dimensionless entrance pressure rates in groove pipe.

On the other hand, it is observed that the value of τ^* reached is much higher in the grooved pipe, when compared to the dimensional stress value observed in the smooth pipe. A possible reason that explains this difference may be related to the effects of the wall slip phenomenon, since in the grooved pipe the movement restriction offered by the geometry is higher.

Conclusions

The restart of a thixotropic fluid in pipes with different surfaces has been studied. The shear rate tests show that for low values, the breakdown and reconstruction process are the possible cause of a behavior that contrasts with the shear rate values greater than 1 s^{-1}. However, after a sufficiently long time, the values tend to an almost constant shear stress value. Then, with the stress values obtained from the constant shear rate tests, the flow curve obtained shows a non-monotonic behavior, due to non-sheared regions caused by an apparently shear banding phenomenon.

In the pressure imposition tests, the behavior of the dimensional stress as a function of time for dimensionless input pressure shows that as the external force increases, an increase in the dimensionless stress is observed. Then, when the shear stress value exceeds the yield stress, a sudden collapse of the microstructure associated with the avalanche effect is observed. The contrast between the dimensionless stress values is influenced by the type of pipe surface and also by the presence perhaps of the slip phenomenon.

These first results show that the flow restart behavior of a thixotropic fluid can be affected by various phenomena, such as avalanche effect and wall slip. The results of more dimensionless pressure values and flow visualization are expected to reveal and somehow quantify the effects of phenomena like wall slip for example. It is also possible to carry out an analysis of the avalanche effect considering the different surfaces and trying to correlate both phenomena with the effects on the minimum reset pressure that can be used to restart flow in gelled fluids.

Acknowledgments

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Responsibility Notice

The authors are the only responsible for the paper content.

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