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WAXY CRUDE OIL FLOW RESTARTABILITY

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Abstract. *Under the hot reservoir conditions, waxy crudes behave like Newtonian fluids but once they experience very cold temperatures on the sea floor, the heavy paraffin's begin to precipitate from the solution impacting non-Newtonian flow behavior to the crude (Chang 2000, Lee 2009, Davidson 2004) and begin to deposit on the pipe wall leave blocked of pipeline. This gel cannot be broken with the original steady state flow operating pressure applied before gelation (Chang 1998). Restarting waxy crude oil flows in pipelines is a difficult issue because of the complex rheological behavior of the gelled oil. Indeed, below the WAT, the gelled oil exhibits viscoplastic, thixotropic, temperature-dependent, and compressible properties due to the interlocking gel-like structure formed by the crystallized paraffin compounds and the thermal shrinkage of the oil. The main objective of this work is to determine the minimal pressure to restart the flow, and the relationship between the fluid rheology , pipe geometry and the restart pressure of the flow. Experiments will be performed to investigate the displacement of carbopol aqueous solutions (viscoplastic fluid without thixotropic effects) by Newtonian oil flowing through a strait pipe to validate the experimental apparatus. Therefore, tests will be made with different fluids, like Laponite and waxy crude oils.*

Keywords*: Waxy crude oil, paraffin, rheology, restart.*

1. INTRODUCTION

The offshore industry requires continued development of new technologies in order to produce oil in regions, which are inaccessible to exploit with the existing technologies. Sometimes, the cost of production with the existing know-how makes it unattractive. With the depletion of onshore and offshore shallow water reserves, the exploration and production of oil in deep water has become a challenge to the offshore industry. Offshore exploration and production of minerals is advancing into deeper water at a fast pace.

The progression of production placed in waters worldwide though the year is illustrated in Fig. 1 (Source: Offshore Magazine). This figure also shows the progression of drilling and subsea completions. It is interesting to note from this figure, the gap between drilling and production. For example, the first drilling in 2000 ft of water took place in 1975. However, the first production from this water depth did not occur until 1993.

For the wells with wet completation, the platforms and the wellhead are not in the same vertical axis, what carts the installation of piping rigid or flexible from the Christmas tree to the platform. Like this, the oil goes out relatively of the reservoir with pressure and temperature discharges, for instance, 80°C and 200kgf/cm2. When reaching the wellhead the oil is cooling and the temperature can decrease to 60°C and with a pressure of 120 kgf/cm^2. Soon after, in traveling from the wellhead to the platform, the oil follows catching a cold, arriving to the platform with an approximate temperature of 14°C and 10kgf/cm^2 of pressure (Spinelli 2009). This cooling is due to heat transfer that happens in the wall of the pipeline, of the oil for subsea water, what always meets in a smaller temperature than the oil. This due to the decrease of the temperature of the water with the depth. Simultaneously, density is going increasing until reaching the maximum value. In Brazil, this fact happens approximately in 2000m of depth and with 4°C. At this depth, the water temperature is constant in 4°C independent of the depth. This cooling happens so much in the production line as in the subsea pipelines done to transport the oil for a terminal in earth.

The cooling has influence in the flow characteristics of oil, particularly if the waxy crude oil is produced (Chang 1998). In this class they are the light oils, with high pour point, with degree API 31,1 and low density, but particularly sensitive to the temperature (Thomas 2001). When trying low temperatures for some time in the sub sea, with smaller temperatures than the wax appearance temperature (WAT), some wax will deposit at the inner side of the wall of the pipeline and some will precipitate in the bulk oil phase as gel and become solid like (Chang 2000, Ekweribe 2009, Warhaugh 87), the precipitation waxy crude follow sequence in the pipeline:

- Solidification.
- Migration for the walls of the tube.
- Deposition in the walls of the tube.
- Deposit more and more thick.

- Blocked partially or total.

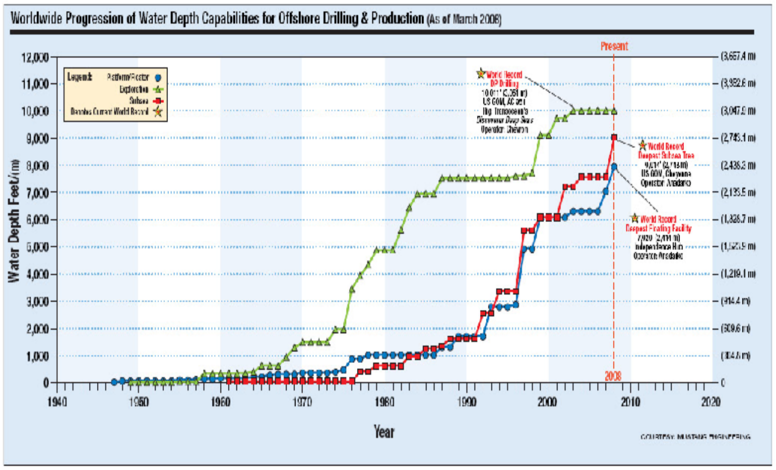


Figure 1. World wide progression of water depth capabilities for offshore drilling & production.

In matter, the total blockade of the pipeline is the starting point for the accomplishment of the present work. With the pipeline blocked by the gel oil, the viable exit for the restart of the flow is the increase of the pumping pressure in order to break the structure of the gel and to continue with the operation of the line usually. Other actions are made to avoid this problem type, as the installation of thermal isolations, depressive of the pour point, crystal modifiers, inhibitors and good pig frequency. Already the removal of blockades partial or total is made with the system of generation of nitrogen (SGN) and with the electric heating of the line, being these last very expensive operations.

Chang-Boger and Nguyen (2000) affirm that the pipeline that transport waxy oils can blocked or stops regularly in the production due to operational stops or you cause for emergency, such as potency failures, earthquakes or damages in the line. In these cases, as it was already said previously the hot oil in the line can cooling static below the pour point (PP), taking to the formation of strong imbedded nets of waxy crystals in the oil.

The main objective of this work is to determine the minimal pressure to restart the flow. This knowledge allows the reduction of production costs, risks of blockages of the line and enables the development of an improved design of pipelines (Thomason 2000). The aim of this study is to determine the relationship between the rheology of the fluid, the geometry of the pipe and the pressure required for the resumption of the flow.

2. BACKGROUND

Perkins and Turner (1971) analyzed some of the factors that affected the behavior of the waxy crude oil. They calculate a yield strength of the gel $\tau = D^* \Delta p / 4L$; but did studies describe this equation as quite oversimplified, yield strengths determined this way can reveal the qualitative effects of variables on gel behavior. They studied the thermal history, the shear history, the aging and the composition. They concluded that the most dramatic effect of the thermal history is shown by cycling the temperature to an intermediate value, back to a higher value and finally to a low testing temperature, such temperature cycling can lead to appreciable increase in yield strength. On the aging of the sample they thought the gel behaves as a tixotropic fluid. Finally, the mixing of a sample of high-yield-strength oil with a large quantity of beneficiated oil at the same temperature will create a mixture with a yield strength very nearly like that of the. Moreover, the gelled crude behaves as a pseudoplastic material to very low values of shear rate, but its behavior grades into a Newtonian-like behavior at high shear rates.

Smith (1978) it describes that the yield stress of the Sea of the North crude under shutdown pipeline conditions can be studied appropriately in the laboratory using model pipelines. A 15m x 6mm bore stainless steel pipe is a fairly large piece of apparatus to immerse in temperature controlled. A period of at least 10 hours soaking at the test temperature is then required and the yield stress of the gelled oil is then tested by applying pressure at one end of the pipe starting at a low pressure and increasing in steps up to the point where flow is detected from the open end of the line. His analysis many factors which all too easily lead to erroneous, belonging one to them, or maybe, the most important the treatment of the oil sample. At a low temperatures in the non-Newtonian region the oil's behavior is largely determined by the structure and quantity of waxy which has come out of solution. The size and shape of the waxy crystals and the forces of attraction between separate crystals are very dependent on previous rate cooling, temperature and shear history.

In order to know the properties of the waxy crude oil, Wardhaugh and Boger (1987) presented measurements done in cone and plate geometry, the concentric cylinders viscometer and the vane technique. In this study, discussed that the cone and plate geometry is that a constant shear rate is maintained throughout the sample, making this geometry particularly suitable for studying time-dependent flow properties. In this experimental work, they found that the fluid sample contracts evenly away from the perimeter therefore reducing the contact area with the plate and hence reducing the torque. They detected that the large volume of sample beneath the bob in this and many other concentric cylinder systems contributes significantly to the problem. The smallest change in temperature while the sample is static (unsheared) however, leads to a dramatic increase in yield stress. Additionally, they detected that the extreme sensitivity of the yield stress to small temperature fluctuations and the rapid breakdown of the structure upon yielding would account for most of the poor reproducibility. Finally, they found that three quite distinct zones occur in an operating pipeline, the first section with the oil is behavior as a Newtonian fluid, the second section the oil is time-dependent, shear and temperature history dependent and behavior non-Newtonian fluid, and the third, where the structure of the oil does not time-depend but it conserves a behavior non-Newtonian fluid.

Wardhaugh and Boger (1991) discussed four classes of oils parafínicos in order to understand the behavior of the properties of the flow. Like this, they developed experimental techniques to obtain good reliability levels in the measurements in viscometer, for instance, the pré-heating of the sample to liberate of the thermal and shear history. As it was observed in the previous study, the oil crosses for three states mentioned already. In the third section where the experimental works have to be accomplished, as it is in this where the fluid has a constant viscosity. They found that the manipulation of the sample affects the final data of the experimental works directly. Moreover, they observed that the flow properties are also dependent of the shear history of the sample. They also showed that in the studies done by Ford, Ells and Russell (1965), in this work they recognized that the viscosity changed with the thermal and shear history and chose a test shear rate equal to 8V/D (the wall shear rate for Newtonian fluids only). The resulting single value of viscosity was then used in the Hagen-Pouisuelle: $\Delta P/L=\mu^*(8V/D)^*(4/D)$. Finally, they concluded that the Dogge-Metznet, modified to account for the effect of the shear history, is preferred over the method of Ford, Ells and Rusell, due to its ability to handle non-Newtonian properties and the resulting shift in the laminar to turbulent transition point.

The same year, Wardhaugh and Boger (1991), made measurements to obtain the yield stress of the waxy crude oil. The study examines the nature of the yielding process techniques, the vane techniques, the application of a constant rate of rotation, the application of a constant shear stress, and oscillatory testing. It is show that the rheological pattern for yield stress materials, but rather is characteristic of the fracture of solids. They also found that the yielding behavior of waxy crude oil is accompanied by three distinct characteristics, an elastic (Hookean) response, a slow deformation (creep), leading to a breakdown of structure fracture-like, and fracture-like behavior resembling the fracture of solids. Finally, they affirmed that the vane technique and the cone and plate viscometer is provided an order of magnitude agreement in the measurement of the fracture stress. Even with correction, the measurement of fracture stress obtained using the vane technique is still 50%-75% of the obtained in the cone and plate viscometer in which modified surfaces are used to avoid wall slip.

Arienka and Ikoku (1994) developed a method to calculate the restart pressure after a long stop in the flow with gel of waxy crude oil. Os authors gave other focus when considering the fluid doesn't eat a plastic of Bingham model, except with the power-law model. The method is iterative as the rheology of power-law crudes is highly temperature dependent. Like this, was the restart pressure flow considered as $\Delta P = 4\tau\ L/D$ that was implemented in *Pipeline Níger Delta*. The diameter predicted using the total pressure drop is smaller than that of the conventional method for non-waxy crude oils.

Chang and Boger (1998) analyzed the yielding process of statically cooled waxy crude oil. They made measurements with three different methods, a controlled stress test, a creep or recovery test, and the oscillatory test, was employed using a controlled stress rheometer. Their results showed that yielding of waxy crude oil occurs by initial elastic response, followed by viscoelastic creep and a final fracture. A model with an elastic-limit yield stress, a static yield stress, and a dynamic yield stress (Fig. 2, source: Chang and Boger 1998) was introduced to describe the yielding process. Moreover the definitions, they shown from both the creep-recovery and oscillatory tests that the elastic-limit yield stress were independent of the time scale. The static yield stress was found to be dependent on the time scale in the three tests. The dynamic yield stress measured only with the controlled stress test was also found to be dependent on the time scale of the yielding. They obtained a good reproducibility can be obtained in these tests by strictly controlling the thermal and shear history of the samples.

Continuing with his work, Chang, Boger and Nguyen (2000) studied the effect of the thermal history on the waxy structure of two statically cooled waxy crude oils using a controlled stress rheometer for rheological measurements and a microscope to observe microstructure of the waxy crystals. With the decreasing temperature, the oil sample changes from a liquid state, through a viscoelastic gel to a solid-like structure. The results from both studies show that the waxy crude structure strongly depends on both the temperature and the cooling rate; a lower cooling rate leads to more and bigger wax particles and more agglomeration between particles. In the same way, they found that it is necessary three yield stresses for describing the yielding process of the waxy crude oils when the temperature is sufficiently below the pour point. Finally, they observed that when the oils are in a gel state, the shear stress-shear rate relationship may be described by the Casson model. When the oils become solid like, the shear stress *vs* shear rate relationship after yielding may be described with the Bingham equation.

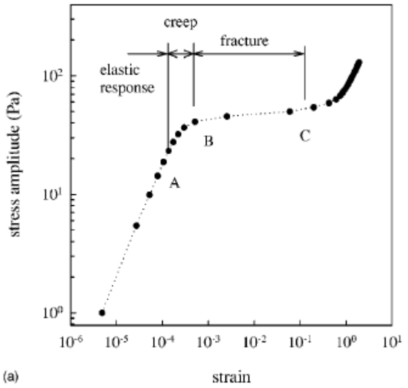


Figure 2. Stress *vs* strain relationship during the yielding process.

Souza Mendez (2008) developed a computational model to determine the conditions necessary for a successful pipeline restart. The analysis considers a viscoplastic material is displaced by another fluid, under the application of a constant inlet pressure. That analysis allows the variation of the entrance parameters, of the geometric characteristics of the tube and of the rheological characteristics of the fluids. Moreover, the work allows calculating the shear stress in the pipeline and the evolution of the flow average viscosity for two fluids in each instant of time. The model used to describe the restart process consists of an incompressible, one-dimensional, and isothermal flow of two fluids in a tube, and the gravitational force is neglected. The simulation takes into account the function viscosity proposed by Souza Mendes (2007) for viscoplastics liquids. In the study, four cases were analyzed, characterized by different combinations of rheological parameters that govern the problem. He found that behaviors radically different, they happen depending on the combinations of values of the parameters and that these differences are linked to the relationship among the viscosities of the fluids.

Ekweribe and Civan (2009) analyzed the pressure and temperature effects on gel strength. They studied the influence of testing temperature on gelation kinetics is studied using a controlled stress rheometer (CSR), using a model pipeline system. They considered that depending upon the cooling rate; the formed gel shrinks with cracks in the middle of the pipe (fast cooling) or at the pipe wall (slow cooling). This process results in compressibility effects during pipeline restart. In the same way, they consider o waxy crude oil gels are viscoplastic in mature and exhibit time-dependent Bingham plastic flow behavior during restart under imposed constant pumping. They describe the models pipeline test as the most common laboratory method resorted to in gel strength measurement because of its geometrical resemblance to the real pipeline. In such tests, gel is formed under controlled conditions (cooling rate, aging temperature, etc.) and pressure is then slowly applied on one end of the gel until flow is observed. The gel strength (τ) is then calculated by $\tau=\Delta P/4(L/D)$. Three sceneries studied on the model pipeline system, gel break at constant injection rate after bleeding the system, gel break at constant injection rate after bleeding the system, and gel break at constant shear stress ramp rate after bleeding the system. For the first case, pressure was applied at the front end and, once the gel broke, the monotonously increasing pressure curve began to fall because the differential pressure between the front and back ends of the tubing began to drop. For the tests after bleeding the system, the outlet valve was open to the atmosphere and, because the whole region after outer valve was filled with mineral oil, the sudden decline in the pressure/time curve at gel break coincided with the drop of effluent oil at the outlet, pushed by the broken gel. They noted that of the ambient tests were conducted at elevated pressure, this was because, in the absence of pressure, compartmentalization of the in the pipeline resulted in multiple gel breaks within the system observed as multiple peaks in the restart pressure profile resulting in a poor reproducibility in the experimental. They discussed that at higher super cooling (7°C/h), the elastic modulus of a gel increases indicating a stronger gel structure. At elevated system pressure, gelation temperature of waxy crude increase while its elastic properties reduce forming a weaker gel. A power-law relationship exists between system pressure and yield pressure for give waxy crude when the pipeline is bled before restart. While the time required for breaking the gel decreases as a logarithmic developed at ambient conditions to subsea systems would lead to over estimation of yield pressures, which, in turn, could lead to excessive spending on pipe design and surface equipment and hamper project economics.

3. MATHEMATICAL EQUATIONS

The fully developed laminar flow in a tube was first studied by G. Hagen in 1939 and by J. L. Poiseuille in 1940. The fully developed flow refers to a region sufficiently far from the entrance causing the flow is axial, $V_Z \neq 0$, while v_θ are void and v_r. Neglecting gravity, and assuming axial symmetry, $\delta / \delta\theta = 0$. Thus, in the runoff and supplement developed for the equation for Newtonian fluid flow in volume (Fox 2001), we obtain:

$$Q = -\frac{\pi R^4}{8\mu}\left[\frac{-\Delta p}{L}\right] = \frac{\pi \Delta p R^4}{8\mu L} = \frac{\pi \Delta p D^4}{128\mu L} \tag{1}$$

For Non-Newtonian fluids the equation of the flow is obtained by the equation Power Law of the volume flow, like this:

$$Q = \frac{\pi R^3}{\frac{1}{n}+3}\left[\frac{(P_0-P_L)m}{2KL}\right]^{1/n} \tag{2}$$

For n=1 and m =1 this is reduced á equation of Hagen Poiseuille flow (eq. 1) (Bird 1978). These equations are valid only for laminar flow, in other words, whenever the number of flow Reynolds is smaller than 2100 (White 2003). The tension in the wall in the pipe is given by the equation:

$$\tau_{parede} = \mu \left|\frac{\partial v_z}{\partial r}\right|_{r=R} = \frac{4\mu V_{med}}{R} = \frac{R}{2}\left(-\frac{dp}{dz}\right) = \frac{r}{2}\frac{\Delta p}{L} \tag{3}$$

The materials that are characterized by the of Bingham model when submitted to low stress don't flow, unless the stress applied crosses a yield stress, after reaching yield stress the relationship between the shear stress and the shear stress is lineal. Conditions acted in the equations:

$$\begin{aligned} \tau = \tau_0 + \mu_\infty \dot{\gamma} \quad &\text{para} \quad \tau > \tau_0 \\ \dot{\gamma} = 0 \quad &\text{para} \quad \tau < \tau_0 \end{aligned}$$

Where τ_0 is the yield stress, and μ_∞ does the limit viscosity, defined in function of the apparent viscosity in the equations:

$$\eta = \mu_\infty + \frac{\tau_0}{\dot{\gamma}} \quad \text{ou} \quad \eta = \frac{\mu_\infty}{1-\frac{\tau_0}{\tau}} \tag{4}$$

The volume flow in a circular tube is given by the equation:

$$Q = \frac{\pi R^3 \tau_R}{4\mu_0}\left[1 - \frac{4}{3}\left(\frac{\tau_0}{\tau_R}\right) + \frac{1}{3}\left(\frac{\tau_0}{\tau_R}\right)^4\right] \tag{5}$$

Where $\tau_R=(P_0-P_L)R/2L$, $\tau_R \geq \tau_0$ (Bird 1978).

4. EXPERIMENTAL PROCEDURE

The experimental apparatus (Fig. 3) it consists of 3 reservoirs, a valve ITV which will read the inlet pressure of air to the hydraulic circuits, a bath for the control temperature of the sample, a transductor pressure that will measure the pressure restart, a analytical balance to know the volume flow of fluid, and an Lab view interface that will join the information of the transductor pressure and of the analytical balance allowing to analyze the information of the components. The model pipeline test section of the hydraulic circuit put in the temperature bath is stainless steel tubing of 6.35mm of external diameter (1/4in) and of 9,3m of length.

The first stage of the experimental procedure is the validation of the experimental apparatus, that is, to know the obtained data of the bench has good agreement with theoretical data of equations of viscous and laminar flow. These practical data will be compared with theoretical values of pressure fall by the equation of Hagen - Poiseuille (Eq. 1). Due to that we have the geometry pipe, the volume flow, the viscosity fluid (Lubrax oil), can obtain the break theoretical pressure to compare with the real break pressure, obtained by the use of a differential manometer in the inlet and outlet of the tubing steel.

With the experimental apparatus validated by the equation of Hagen - Poiseuille can begin the tests of restart pressure flow. The first work fluid will be the carbopol being pushed by water (this will be pushed by compressed air), this carbopol fluid is viscoplastic material with simple rheological behavior since doesn't have tixotropic characteristics and non-dependent temperature. The carbopol fluid will be pushed from the reservoir ties the coil of steel put in the bath for temperature control, in that point, after some minutes to eliminate the flow inertia, the flow air begun again, the transductor pressure had measured the increase and the maximum pressure value for restart flow that is, in the moment of reaching yield stress τ_0 of the carbopol fluid.

Simultaneously, make the rheological characterization of the carbopol fluid, with the restart pressure data obtained in the tests, the rheological characterization, the geometry pipe, and high levels of reproducibility, is had data then necessary to do the dimensionless of parameters.

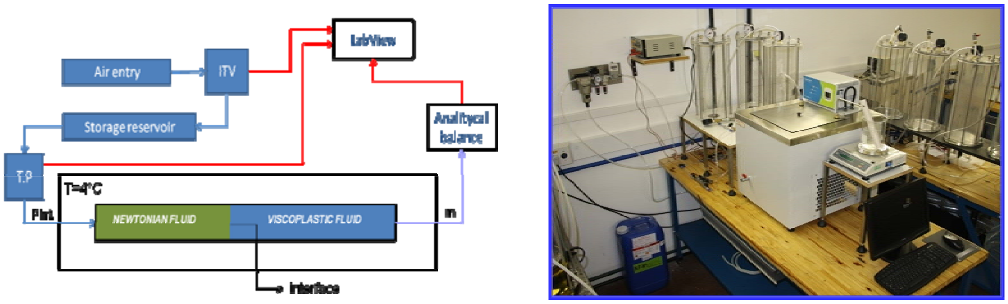
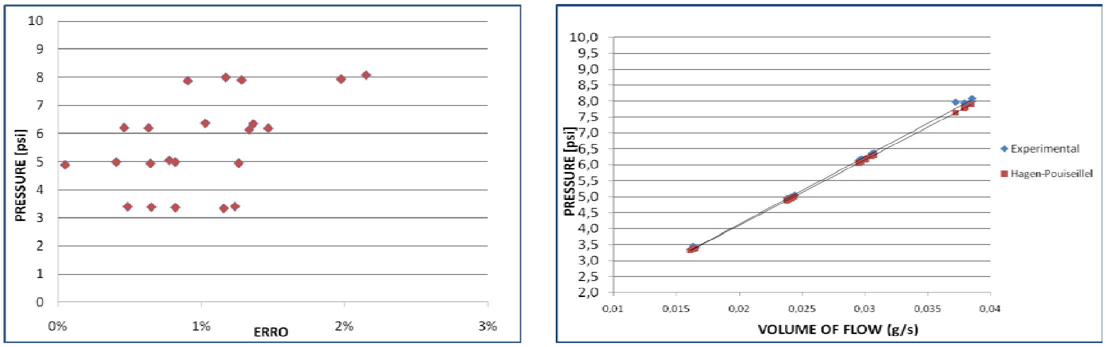


Figure 3. Experimental apparatus.

4.1 Validation

The Figure 4 show the agreement level between the experimental data and the data obtained with the equation of Hagen - Poiseuille. In Fig.4a we have the real pressure and the percentage of mistake of the measurement with the obtained die eats equation, the mistake meets in the strip of 0% and 2,3%, what was considered as a good result. In Fig.4b the pressure and the flow for the two cases, the theoretical and the experimental making the comparison and the good agreement of the data can see.



(a) (b)

Figure 4. Results of validation of experimental apparatus.

5. FINAL REMARKS

The data obtained in the tests with oil Lubrax in the experimental apparatus validation allowed to know the good agreement that has the bench with equation for flow and laminar flow (Hagen-Pouseuille) being a good starting point for begin of the tests with Carbopol fluid. The experimental data of the tests of restart allowed to know the pressure necessary for begin to flow *versus* the time, in order to obtain real relationships of these values with the flow geometry and the rheological fluid characteristics. Moreover, it had been studied influences of the pressure applied pressure intensity *versus* the restart pressure , that is, the pressure application changing the time of application that had provided bases to know which is the best procedure in the restart pipeline.

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