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EXPERIMENTAL STUDY OF START-UP FLOWS OF GELLED WAXY OILS IN PIPELINES – A REVIEW

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Abstract. Oil dependence allied with the discovery of large reserves in ultra-deep regions, such as the Brazilian Pre-salt basin, motivates the research to overcome technological challenges inherent in the production and transportation of oil. The petroleum is mostly composed of paraffinic hydrocarbons. The oil reservoirs are located in regions up to 7000 meters deep regarding to the surface of the sea. The pressure and temperature in these reservoirs can reach values of 100 MPa and 150 ºC, respectively. The production and transport of oil from these basins to the coast occurs through pipelines. The seabed in which the pipes are placed is at a temperature of approximately 4 °C. Then, during the flow, the oil may cool down due to the temperature gradient. The reduction of the oil temperature causes crystallization of the paraffin crystals. This is associated to some problems, such as: the deposition of paraffin at the wall, the gelation of the oil and the increase of the viscosity. Several authors have researched the gelation of the oil and the flow restart using different experimental apparatus and procedures to restart the flow. In these papers, the rheological properties of the oils, such as temperature, rate of change of temperature, shear rate, aging time and restart pressure, were evaluated. The complex behavior of paraffinic oil makes it difficult to understand the influence of each rheological parameter during the restart process. So to facilitate the understanding of these parameters a study of viscoplastic fluids will also be performed. Therefore, the objective of this paper is to conduct a review on flow restart of paraffinic oil and Carbopol studies in order to understand better the transient phenomenon of flow restart.

Keywords: Start-up flow, Experimental apparatus, Viscoplastic fluids, Waxy oils.

1. INTRODUCTION

Oil is a non-renewable energy resource that is very widespread in society. It is fundamental in the sectors of transport and industry, and it is being a raw material for the production of plastics, solvents, fertilizers, synthetic rubbers, among others (Petrobras, 2017). In the period between 1970 and 2015, oil represented more than 25% of Brazil's energy supply, which shows the importance of this product over the years (IEA, 2016). The dependence on oil and the discovery of large reserves in ultra-deep basins, such as the Brazilian pre-salt, motivate the research to overcome the technological challenges inherent in the production and transportation of oil in regions of great depth.

The pre-salt reservoir in the Brazilian coast is 200 kilometers wide with more than 7,000 meters of depth and extends from Santa Catarina to Espirito Santo (Pré-sal Petróleo, 2017). These reserves have high temperatures from 70 to 150 °C and pressures from 50 to 100 MPa, while the pipelines that transport the oil from the reservoirs to the coast are placed over the seabed whose temperature is approximately 4 °C (Venkatesan et al, 2005). Because of the heat exchange between the oil and the ocean, there is a reduction in the oil temperature, which causes the solubility of the hydrocarbons to be reduced.

According to Zílio & Pinto (2002), Brazilian oil may have up to 90% paraffin in its composition. It is known that the decrease in the solubility of hydrocarbons promotes the precipitation of paraffin crystals in oil when it has a temperature below its crystallization temperature[1]. Under these conditions, the behavior of the fluid changes from Newtonian to non-Newtonian (Venkatesan et al., 2005). This phenomenon is associated to the accumulation of paraffin crystals on the internal surface of the pipelines, and it may cause an increase in the pressure loss in the pipeline and decrease of the flow rate. Andrade et al. (2015) showed that the viscosity increased two orders of magnitude due to the

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[1] Crystallization temperature is the temperature at which the precipitation of crystals begins in the paraffinic oil (Andrade, 2017).

reduction of the initial cooling temperature of the oil. The procedure performed in their study was the variation of initial cooling temperature values from the crystallization point of the oil up to 4 ºC.

Moreover, another inconvenience is the gelation of the oil, which is characterized by the structuring of the crystals to form a gel. This process happens in eventual shutdowns or during production and transportation of the oil. It is emphasized that for the material to behave as a gel is necessary to have only a concentration of 0.5% by mass of paraffin precipitated (Yao et al., 2016). When the oil is gelled in the pipeline, high pressures are required to break the gel and to start-up the flow (Magda et al., 2013). Therefore, accurately predicting the pressure required to start the flow is important, since overestimating the pressure requires the use of more robust pipes, which can make the project unfeasible due to the high investments needed. (Oliveira & Negrão, 2015).

The flow restart phenomenon in pipeline with gelled paraffinic oil is divided into four stages: pressure propagation through the pipeline, yielding of the oil, breakage of the gel structure and restart of flow (Uhde & Kopp, 1971). During these stages, the behavior of the gelled oil exhibits several non-Newtonian characteristics, such as: visco-plasticity, elasticity, time dependence and thermal and shear histories (Tarcha et al., 2015). These characteristics acting together in the oil make it difficult to understand the influence of each isolated characteristic on the overall behavior of the material.

Several authors have published papers regarding to the parameters that influence the rheological properties of paraffinic oils, such as: temperature (Davenport & Somper 1971; El-Gamal 1998; Visintin *et al.* 2005; Rosso 2014; Andrade *et al.* 2015), cooling rate (Rønningsen 1992; Kané *et al.* 2003; Venkatesan *et al.* 2005; Visintin *et al.* 2005; Lee *et al.* 2008; Rosso 2014), shear rate (Davenport & Somper 1971; Kané *et al.* 2003; Venkatesan *et al.* 2005; Lin *et al.* 2011; Andrade *et al.* 2013), aging time (Chang *et al.* 2000; Visintin *et al.* 2005; Andrade *et al.* 2015; Rosso *et al.* 2015). Besides, other experimental studies evaluating the pressure required to restart the flow (Smith & Ramsden 1978; Rønningsen 1992; Ekweribe *et al.* 2009; Peerapornlerd *et al.* 2014; Van der Geest *et al.* 2015; Jemmett *et al.* 2013; Magda *et al.* 2013; Rosso 2014) were conducted. In these studies, the authors evaluated the four stages of the restart separately and together in an attempt to understand the whole mechanism of the process.

Therefore, in order to better understand the influence of the variables on the flow restart process of gelled oil, this paper reviewed the main researches carried out in this area. The focus were mainly in the studies that used experimental apparatus, since it has more similar conditions to the real ones. To facilitate the understanding of the rheological characteristics of oils, it was reviewed the restart of flow with a less complex fluids, the Carbopol which is considered as a viscoplastic fluid.

2. EXPERIMENTAL EVALUATION ON THE RESTART FLOW

It is known that the main feature of a viscoplastic fluid is its yield stress. Due to this characteristic this material behaves as a solid-like if is not sufficiently stressed, otherwise the material flows like a fluid, if the yield stress is exceeded. This kind of fluid that presents a variable viscosity as a function of the shear rate are called non-Newtonian fluids. These fluids do not follow Newtonian behavior. In order to represent mathematically the physical behavior of these fluids and also to validate the experimental results of the tests, constitutive relations such as the Bingham and Herschel-Bulkley models are used.

According to Balmforth et al. (2014), the aqueous solutions of Carbopol presents a behavior similar to the ideal viscoplastic fluid. These fluids have a less complex behavior than paraffinic oil (Sestak et al., 1987). Thus, it was decided to analyze experimental papers of Carbopol solutions initially, in order to facilitate the understanding of the rheological behavior of the oils.

2.1. VISCOPLASTIC FLUIDS

Taghavi et al. (2012), Alba et al. (2013) and Gaona Sierra et al. (2016) performed an evaluation of the flow restart in pipelines with viscoplastic fluids. Taghavi et al. (2012) analyzed the displacement of an aqueous solution of Carbopol by a Newtonian fluid, in a slightly inclined pipe. The authors observed that two types of flow occurred predominantly, one characterized by a central type flow and the other by the slump flow. In the first type, Carbopol flowed mainly through the center of the pipe. And in the second one, the Carbopol flow was divided in two fronts, a small front with higher velocity travelled through the bottom of the pipe, followed by the larger front with slower velocity through the rest of the pipe. In both flows, static fluid layers were observed due to the high yield stress of the viscoplastic fluid. The transition between these above flows occurred for critical reasons between the Reynolds (Re [2]) and Froude (Fr [3])

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[2] Reynolds number is a dimensionless number defined as the ratio of inertial forces to viscous forces (Pritchard, 2011)

[3] Froude number is a dimensionless number defined as the ratio of the inertia forces to gravity forces (Pritchard, 2011).

numbers of $600 < \text{Re}/Fr < 800$. It was observed that for Re/Fr below 600, the central flow was predominant. On the other hand, for ratios above 800 the slump flow occurred.

Proceeding with the work of Taghavi et al. (2012), Alba et al. (2013) studied the displacement of the yield stress fluids in highly inclined pipes. The authors observed for a full range of the pipe inclinations (0 - 85°) that both central-type and slump displacements occurred. Besides that, for the slump flow a few odd behaviors were noticed at higher inclinations, which was associated to the yield stress of the Carbopol. These conclusions implied that the inclination angle was determinant to the secondary flow behavior in the slump flow, however it did not dictated the flow regime.

Gaona Sierra et al. (2016) evaluated the restart flow of a viscoplastic material being displaced by a Newtonian fluid in a roughened pipe, which was used to avoid fluid slippage. The authors observed that the restart occurred with delay and they also noted the presence of the avalanche effect. This response indicates that the material presented elastic behavior, and temporal dependence. In addition, the authors showed that as the pressure rate increased, the delay time decreased and the velocity of the displacement increased. Therefore, the clearance time of the line was reduced. It should be emphasized that the incoming fluids that presented the highest viscosities also had the lowest displacement velocities.

Coussot (2014) reviewed the yield stress fluids under several conditions, such: uniform flow in straight channels, complex flow in channels of varying cross section area (flow through porous medium, extrusion, expansion), and transient flows (spreading, spin-coating, elongation and squeeze flow). The author highlighted the difficulty of predicting the flow characteristics of these materials, due to the presence of the solid and liquid behaviors. The main discussions were about the influence of the deformations in the solid regime to the transient flows, the nonappearance of the yield characteristic for large imposed deformations and the absence of the yield character in secondary flow.

Mitishita (2017) studied pressure transmission in Carbopol and glycerine solutions in a serpentine-shaped pipe. For glycerin (Newtonian fluid), the pressure was completely transmitted and also showed a uniform behavior. This behavior of the pressure profile is due to the low viscous dissipation of the glycerin, which leads the pressure to propagate fast. Conversely, for the Carbopol solution, it was observed that the pressure transmission was not uniform under constant pressurizing, i.e., the pressure gradually increased from the upstream to the downstream of the pipe as the yield stress of the material was exceeded. For this viscoplastic fluid, the viscous dissipation was higher, and as a consequence the propagation was slower. In addition, the author concluded that under low pressurization (3 bar), Carbopol's shear history may influence the pressure distribution in the pipe. Also, that the higher the yield stress of the viscoplastic fluid, the less pressure is transmitted along the pipe.

Liu & de Bruyn (2018) studied the effect of smooth and rough-walled pipes on the flow restart of Carbopol. The displacement of the viscoplastic fluid was performed by a Newtonian fluid from the bottom to the top of a vertical pipe. For the plain tube, the authors observed that the shear stress in the wall did not exceed the yield stress. While for rough pipes, fluid flow occurred with the following steps: elastic deformation, start of slippage, followed by detachment of the fluid from the wall, and finally, plug flow at steady state. This study reiterated the importance of the elasticity during the beginning of the restart and for the cases where the applied flow rate was around 5×10^{-7} m^3/s, there was a predominant contribution of elastic stress in the shear stress on the wall, which did not occur for lower flows (5×10^{-8} m^3/s).

2.2. WAXY CRUDE OIL

The study of the restart flow with gelled paraffinic oil has been analyzed from different experimental apparatus in laboratory scale, using samples of oil from different regions and model waxy oil, in order to reproduce the conditions found during the extraction and transportation of petroleum at the bottom of the sea. This phenomenon was investigated by several authors, among them: Smith & Ramsden (1978), Rønningsen (1992), Borghi et al. (2003), Guozhong & Gang (2010), Phillips et al. (2011a), Phillips et al. (2011b), El-Gendy et al. (2012), Jemmett et al. (2013), Magda et al. (2013), Luthi et al. (2013), Fossen et al. (2013), Rosso (2014), Van Der Geest et al. (2015), Kumar et al. (2016).

In the evaluation of the gelation process carried out by Smith & Ramsden (1978), it was observed that the occurrence of this process was delayed. The explanation given by the authors is that the initial cooling temperature of the oil influenced the behavior due to the presence of asphaltenes and resins in its composition, and these components interacted with the wax crystals. However, this phenomenon has not been reported much in the literature, and the causes of this phenomenon are not well understood.

Rønningsen (1992) compared the results of minimum pressure required to restart the flow obtained in an experimental apparatus with those of a stress-controlled rheometer, evaluating ten samples of North Sea oil. The conclusion of this work was that despite of the difference up to 15% between the values of yield stress obtained by the two instruments, the results of the rheometer in the condition of 5 K/min and stress-loading rate of 2.5 Pa/min with low aging time could be used as a complement to the experimental apparatus data. Similarly, Lee et al. (2008) also observed that the results of the rheometer (stress controlled) predicted the pressure to break the gel in the pipe with a cooling rate of 3.5 K/h.

According to Lee et al. (2011), the reason for the difference in results between the rheometer and the experimental apparatus in transient regime is due to non-uniform pressure distribution within the pipe. This non-linear behavior profile is consequence of compressibility and thermal shrinkage, which cause the formation of voids between the gel and the pipe. Besides, this voids cause the decrease of the effective contact area of between the gelled structure and the wall thus

reducing the shear stress on the wall. Then, the restart occurs at a lower pressure than that predicted by the rheometers. Borghi et al. (2003) and Luthi et al. (2013) also reported this phenomenon.

Ekweribe et al. (2009) concluded that the application of a constant high pressure during the cooling, promoted the formation of gels with weaker structure, which reduced the time and pressure required for the restart occur. It is highlighted that this work is the only one to suggest this hypothesis. Furthermore, the author noted a power law relationship between the pressure applied in the system and the restart pressure, when the pipe was bled before restarting. This indicated that the time for breaking the gel decreased in the form of a logarithmic function of the pressure required for the restart.

Fossen et al. (2013) observed that the application of high cooling rates in the oil promotes the formation of less resistant structures. The explanation for this behavior is because the precipitated paraffin does not form a gelled structure inside the oil, it only accumulates in the bottom of the pipe. Otherwise, in the application of low cooling rates, the formation of more resistant microstructures occurs due to the better accommodation of the crystals in the gel (Visintin et al., 2005, Lee et al., 2008, Ekweribe et al., 2011, Fossen et al., 2013).

Peerapornlerd et al. (2014) concluded that there is a reduction of the pressure required to restart the flow in one order of magnitude when the flow is stopped at a temperature of up to 5 °C below the Wax Appearance Temperature (WAT) compared to the stop condition occurring at the temperature above the WAT.

Wei et al. (2016) explained the stages of formation of gas voids within the gelled oil during the cooling. When the oil temperature dropped below the WAT, the wax begins to precipitate in the pipe. Then, when the oil reaches the temperature below its pour point[4], the gelled oil matrix is already formed along with the voids. It is important to highlight that in this process, the thermal shrinkage led to the formation of voids in the gelled structure.

Phillips et al. (2011), Fossen et al. (2013) and Van der Geest et al. (2015) evaluated the shrinkage of the oil during the cooling process and the appearance of gas voids within the pipe. In this study, a proportionality ratio was observed between the analyzed variables, as the cooling rate was getting higher, the sample retraction and the pressure gradient in the pipe were higher. This behavior was similar to the ones observed by Magda et al. (2013) and Rosso (2014). Magda et al. (2013) noted that when the oil temperature passed through its pour point, there was a decrease of the pressure in the pipeline because of the oil contraction during the cooling. Furthermore, Rosso (2014) observed an increase in time to the pressure overshoot to occur and for the gel to be removed from the pipe. Moreover, the shrinkage rate also may induce the occurrence of cohesive failures in the gel, specifically in low-pressure locations as pointed for Phillips et al., 2011b. It should be pointed out that cohesive failure is the breakdown in the internal part of the crystalline structure, while adhesive failure is the breakdown in the surface between wall and gel.

Jemmett et al. (2013) compared the behavior between the matrix of homogeneous and heterogeneous gel structures. Such gels are formed during the shutdown that occurs followed by cooling below the gel point of the oil. Homogeneous paraffinic oil is characterized to have no pre-existing sheared crystals in the fluid during the flow closure period. On the other hand, the heterogeneous has pre-existing sheared crystals at shutdown. The authors concluded that gelled structures produced by heterogeneous oil are less resistant than those generated by the homogeneous, when formed under the same conditions. The explanation of this phenomenon is due to the weak interactions between the crystalline lattice, as a consequence, there is occurrence of internal cohesive failures of the material. This phenomenon was confirmed by the PIV (Particle Imaging Velocimetry) technique, which proved that there is a cohesive failure at the center of the gel for all the applied load pressure rates. Yet, the PIV showed that the interaction between gel and wall was not altered, only the center of the gel structure changed. Moreover, this study suggests that the particle size of the molecule of the heterogeneous gel appears to have no meaningful influence on the magnitude of the restart pressure, for a range from 6.7 to 12 μm of mean circular diameter.

Similarly, Lee et al. (2008) evaluated experimentally the delimitation between cohesive failures and adhesives failures of gelled oils. The authors point out that the formation of these failures depends on the cooling rate, i.e., the influence of the cooling rate over the size, density and shape of the crystals determine which of the failure will occur predominantly.

Regarding the propagation of the pressure wave and the breakage of the gelled oil, Luthi et al. (2013) pointed that the assumption that the restart of flow occurs simultaneously with the moment of breaking of the entire gelled structure is very conservative. As shown experimentally, the break occurs first at the inlet of the pipe, where the pressure is applied, and then it propagates with the pressure wave until the complete breakdown of the gel occurs. The breakdown propagation breakdown of the gelled structure from upstream to downstream was also demonstrated by El-Gendy et al. (2012) using the PIV, and by Lee et al. (2008).

Evaluating the moment just prior to the restart attempt, Magda et al. (2013) concluded that the gelled structure formed under pressurization has an axial pressure profile dependent on the period of time that the flow remained at rest. Thus, at the moment just after the gel was formed, it was observed the greatest wall shear stresses due to the axial pressure gradient from pressurization. On the other hand, after a long period of stagnation, the pressure gradient tended to zero in

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[4] Pour point is the lowest temperature at which the material still flows in a test tube under the action of gravity, considering that the position of the tube is changed from vertical to horizontal.

the gel, because of Darcy's flow, which is the flow of the low molecular weight components of the oil through the gel crystalline network during the rest. However, this last conclusion does not imply the loss of adhesion between the gel and the pipe wall.

Despite studying the gel pressure profile Magda et al. (2013) did not evaluate the pressure required to restart the flow. As Visintin et al. (2005), Luthi (2013) and Rosso (2014) highlighted the longer the aging time of the gel, the higher the pressure to restart the flow. This phenomenon is consequence of the greater time the crystalline structure has to restructure.

In addition, Rosso (2014) investigated some rheological parameters of Brazilian paraffinic oil during the flow restart. Results showed that the increase of the shear rate and the reduction of the cooling rate during the cool down period resulted in low start-up pressures. Furthermore, the author observed that the lower the final cooling temperature, the higher the pressure overshoot. It was further demonstrated that under a given initial test temperature a pressure overshoot was obtained, independent of the application of shear stress in the fluid, i. e., Rosso observed that the initial temperature of 30 ºC led to a maximum pressure overshoot. However, temperatures above or below 30 °C resulted in lower restart pressure.

Fossen et al. (2013) studied the influence of the pipe diameter on the pressure required to restart the gelled oil. This paper calculated the restart pressures for tubes with diameters of 4.3, 28, 55 and 82 mm. Besides, the restart pressures were extrapolated for the same pipes of 28, 55 and 82 mm through the pipe yield stress of 4.3 mm. The extrapolation was done for comparison purposes with the initially calculated pressures. The authors concluded that as the pipes' diameter increase, the yield stress rate does not have the same increase ratio. An explanation for this phenomenon may be the increase in the elasticity of the gelled material due to its larger size and mass. Furthermore, the authors observed that the yield stress estimated by small diameter tubes overestimates the restart pressures for larger pipes, when it is compared with the pressure obtained experimentally in the pipe itself.

Commonly, the authors estimate the pressure required to restart the flow through Eq. 1 to validate their results in experimental apparatus with rheological studies (Røningsen, 1992; Borghi et al., 2003, Lee et al., 2008, Margarone et al. 2010, El-Gendy et al., 2012, Fossen et al., 2013, Kumar et al., 2016). However, the use of this equation can overestimate the pressure required to restart the flow (Fossen et al., 2013; Van der Geest et al., 2015) due to the fact that waxy-gelled oil is considered as viscous fluid, incompressible and single phase (Chala et al., 2018).

$$\Delta P_{\min} = \frac{4\tau_w L}{D} \tag{1}$$

where $\Delta P_{\min}$ is the minimum pressure to restart the flow, τ_w is the wall shear stress, L is the length and D is the diameter. The wall shear stress is determined by rheological experiments as flow curve and oscillatory tests .

This equation must account that due to the void formation during cooling the gelled oil is a compressible fluid. In addition, the presence of the gelled structure with small amount of liquid oil invalidate the single-phase assumption (Chala et al., 2018). So to reiterate the Eq. 1 is a force balance equation and do not contemplate parameters that can also influences the restart such as compressibility, shrinkage of the fluid during cooling and the use of different cooling conditions.

Van der Geest et al. (2015) observed that only the yield stress is not the dominant factor to determine the required pressure to restart the flow, however, compressibility and shrinkage significantly interfere in the magnitude of the restart pressure. The authors indicated that compressibility and shrinkage reduced the pressure required for the restart, since the pressure required to restart the flow in the experimental apparatus was much lower than the pressure obtained by the Equation 1.

Chala et al. (2018) highlighted the importance of quantification and detection of voids in the pipe to accurately predict the restart pressure. A new method that is beginning to be used both to quantify and to locate the voids is the magnetic resonance image (MRI), mainly for its precision.

El-Gendy et al. (2012) evaluated the effect of voids formation on the gelled structure through the pressure profile and the PIV technique. The analysis of this paper consisted in evaluating the application of insufficient pressure after the gelation to restart the flow at the entrance of the pipe, which resulted in a profile of the axial pressure that becomes linear and occurs in two stages. Initially it is characterized with a slight immediate increase of the pressure at the outlet, and then followed by a time-delayed jump. In the initial part, the phenomenon that occurred is associated with the propagation of the pressure wave through the porous internal network of the gel, while the second stage is related to the shear modulus of the gel. The deformation of the gel measured by the PIV also showed the same process of time dependence for the axial pressure profile in two steps. Kumar et al. (2016) showed that the pressure wave during propagation in the pipeline in the flow restart generated an approximately constant pressure gradient, after the flow restart had occurred with a delay time.

Fleyfel et al. (2004) tried to prevent the wax precipitation during the shutdown and steady state regime using an insulation coating on the pipelines however it did not worked. Similarly, Smith & Ramsden (1978) could not avoid the wax precipitation with an insulation under a rapid change in the cooling rate of waxy crude oil.

Guozhong & Gang (2010) evaluated the deposition of paraffin on the walls of the pipe through an experimental loop. The authors observed that due to the instantaneous temperature decrease in the pipe walls there was an increase both in pressure and in viscosity in the layers near the walls. In addition, it is concluded in this article that there is a critical thickness for the deposition layer in ducts with low flow of hot oil flow. The critical thickness varies depending on the pipe diameter, the characteristics of the gelled oil, the temperature condition around the duct and the construction characteristics of the pipe.

Regarding to the flow restart protocol used in the analyzed papers, every procedure followed a order such as: (a) warm up the circuit section, and then fill the line with the fluid at the set temperature; (b) cooling the oil in the test section from the initial temperature to the test temperature for a set time; (c) aging for a fixed period until the gelled oil is formed; and (d) restart the line by applying pressure or constant flow rate through the pump. The main difference in the protocol was in the initial test temperature, the restart pressure and in the pressurizing conditions during cooling and aging of the fluid, which were inherent to each proposed research.

3. CONCLUSIONS

The complexity of the rheological behavior of the crude oils allows these fluids to have a variety of uncommon characteristics. During the flow restart process, the characterization of these properties are even more problematic due to the coexistence of these characteristics with different operational conditions. Therefore, to better understand the behavior of the oil this paper reviewed the flow restart of paraffinic oil and of viscoplastic fluids, which present a less complex behavior.

The main feature of the viscoplastic materials is that it only flows if is submitted to a stress above some critical value (yield stress). Conversely, this material will behave as a solid. The main conclusions of the viscoplastic studies highlighted the importance of the elasticity in the moment before the restart, the influence of the yield stress in the transmission of the pressure and the displacement of yield fluids occurring mainly in central type displacement and slump flow.

Regarding the results of waxy crude oil, it can be summarized as: a) the increase of the shear rate led to low restart pressures; b) the reduction of the cooling rate during the cool down period resulted in low restart pressures; c) the lower the final cooling temperature, the higher the pressure overshoot; d) the longer the aging time of the gel, the higher the pressure to restart the flow; e) the application of high cooling rates in the oil promotes the formation of less resistant structures, on the contrary, the application of low cooling rates results in more resistant microstructures; f) the higher the cooling rate, the higher the sample retraction.

Concerning the use of the force balance equation to predict the restart pressure, it was discussed that it is not reliable method to predict precisely the restart pressure, since this equation overestimate the pressure values. Moreover, some authors verified that the restart pressure of large diameter tubes cannot be estimated adequately by the yield stress of small diameter tubes.

Its is known that to restart the flow it is required to follow four steps: the propagation of the initial pressure wave down the pipeline, yielding of the gel, breaking down until the gel exhibits steady viscosity, and finally clearing the line. As said before, the behavior of the gelled oil during these stages is very complex, as it present features of visco-plasticity, elasticity, time dependence and thermal and shear histories.

So far, there is not many papers studying the flow restart, and even less using experimental apparatus. Therefore, an extensive zone of research remains open to be investigated. A few topics which might be addressed more attention are the shrinkage, compressibility and void formation in order to better understand its influence over the restart pressure.

4. ACKNOWLEDGEMENTS

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