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A NUMERICAL AND EXPERIMENTAL STUDY OF THE PRESSURE TRANSMISSION IN VISCOPLASTIC FLUIDS CONFINED IN PIPELINES

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Abstract: The transmission of pressure applied at the inlet of a closed pipeline filled with a yield stress (or viscoplastic) fluid is investigated in a laboratory-scale experiment. The experimental setup consists of a pump-driven flow loop installed inside a thermally controlled chamber. While the pump pressurizes an aqueous Carbopol solution into a 48.3m helical pipeline closed at the outlet, the pressures are measured and recorded. In contrast to Newtonian fluids, the results indicated that the pressure imposed to a viscoplastic fluid is not fully transmitted along the pipeline. This non-transmission of pressure is related to the fluid yield stress. The experiments are used to validate the mathematical model from Oliveira and Negrão (2015) for the pressure transmission problem in a yield stress fluid. Numerical results for the fluid pressure are within a 5% error band when compared to experimental results, indicating a good agreement.

Keywords: yield stress fluid, pressure transmission, experimental apparatus.

1. INTRODUCTION

One of the properties of drilling fluids is the yield stress. When subjected to stresses below the yield stress, the material does not flow and behaves like a solid, and shearing will only occur when the yield stress is surpassed. This behavior can present some difficulties in drilling operations. For instance, completion valves installed on the drillpipe are actuated by a pressure difference. Differently from Newtonian fluids, in drilling fluids the pressure imposed at the surface is not fully transmitted to the valve's position, which prevents its operation. The numerical study by Oliveira et al. (2012) attributes the failure in pressure transmission to the yield stress. Additionally, inertial forces, viscous dissipation and pressurization rate also play an important role in the final pressure distribution and, consequently, how much pressure is transmitted from the inlet to outlet (Oliveira et al, 2013). These observations indicate that the final pressure distribution after fluid pressurization may be time-dependent.

Water hammer, or the pressure propagation after sudden valve closure during steady flow, is a similar phenomenon to the pressure transmission problem. Most numerical simulations and experiments considered the working fluid as Newtonian (Homboe and Rouleau, 1967; Brunone et al, 1995; Brunone et al, 2000; Wahba, 2008). However, non-Newtonian fluid hammer has been the focus of numerical simulations of a few articles. Wahba (2013) investigated the attenuation of transients in power-law fluids, and Oliveira et al (2016) focused his analysis on viscoplastic fluids. The final pressure distribution after the valve closure was non-uniform, similarly to what was observed in Oliveira et al. (2012).

Flow start-up of waxy crude oil has been widely studied by numerous authors (Sestak et al., 1987; Cawkwell and Charles, 1987; Chang, et al. 1999; Davidson et al. 2004; Vinay et al. 2006; Vinay et al. 2007; Wachs et al., 2009;

Oliveira et al. 2010; Oliveira e Negrão, 2015) with numerical simulations. There have been some attempts to experimentally study the pressure propagation during transient phenomena in yield stress fluids such as waxy crude oils (El-Gendy et al, 2012; Rønningsen, 1992; Sierra et al, 2016), but these accounted for flow start-up situations. Experiments with yield stress fluids are also feasible by employing Carbopol solutions, which behave closely to an ideal viscoplastic fluids, i. e. when thixotropic and elastic effects are negligible (Balmforth et al, 2013). Furthermore, start-up flow experiments were also employed to provide an estimate of the yield stress of crude oils, by converting pressure and flow rate to shear stress and shear rate, respectively (Rønningsen, 1992; Lee et al, 2008). However, to the authors' knowledge, there are very few experimental studies concerning the propagation of pressure in yield stress fluids compressed in closed pipelines.

The work by Oliveira et al. (2013) presented an experimental and numerical investigation of the pressure transmission in drilling fluids compressed in a closed pipeline of a drilling rig by Petrobras. However, repeating those experiments in the conditions specified is next to impossible, due to the lack of control of critical values such as temperatures and fluid properties, and also due to the complexity of the equipment. Thus, laboratory-scale experiments can be employed to better comprehend the phenomenon by means of comparisons to numerical simulations. Specifically, the mathematical model by Oliveira and Negrão (2015) has only been validated with an analytical solution for a flow start-up problem of a Newtonian fluid, and the use of this mathematical model during pressure transmission problems needs verification. The model shall be employed to simulate the pressure transmission problem with a viscoplastic fluid by implementing the properties of the working fluid used in the experiments. Thus, the current work proposes an experimental and numerical analysis of the pressurization of yield stress fluids in a closed pipeline, in order to validate the mathematical model by Oliveira and Negrão (2015) for this specific application. This is done by means of an experimental flow loop with controlled pressures, temperatures and fluid flow-rates.

2. EXPERIMENTAL PROCEDURE

2.1. Description of the experimental setup

Consider the following schematic and photograph presented in Figure 1. The experimental setup consisted of a pump-driven flow loop in a thermally isolated chamber. The helical pump with working pressure range from 0 to 12 bar, displaced fluid to a 20.45 mm in diameter, 48.3 m (axial length) helical pipeline, with four 16 bar pressure transmitters installed on the helical pipeline walls. These sensors were named P1, P2, P3 and P4. Their measurement rate is 500 Hz, with an accuracy of 0.1% of span. The sensors P1 and P2 were 16.3 m apart from each other, P2 and P3, 16 m and P3 and P4, 16 m, considering the length parallel to the pipeline axis. A 50 l tank was used to store the fluid inside the apparatus. On the top cover of the reservoir an electric agitator was installed, so that homogeneous mixtures could be produced.

Flow control was carried out by three electro-pneumatic pneumatic valves: the inlet valve V1, outlet valve V2 and bypass valve V3. Fluid from the reservoir was displaced by a pump to the helical pipeline or the bypass pipeline, depending on the valve configuration. If the inlet and outlet valves are open and the bypass valve is closed, fluid is displaced to the helical pipeline. If the inlet and outlet valves are closed and the bypass valve is open, fluid is pumped directly back to the fluid reservoir through the bypass pipeline. A manual valve (MV) was installed on the bypass as well, allowing for pressure control by flow restriction. A Coriolis flow meter was installed downstream from the outlet valve, with a measurement range up to 1.530 l/s. It was also capable of providing measurements of the specific mass and temperature of the fluid passing through it with a 0.1% uncertainty.

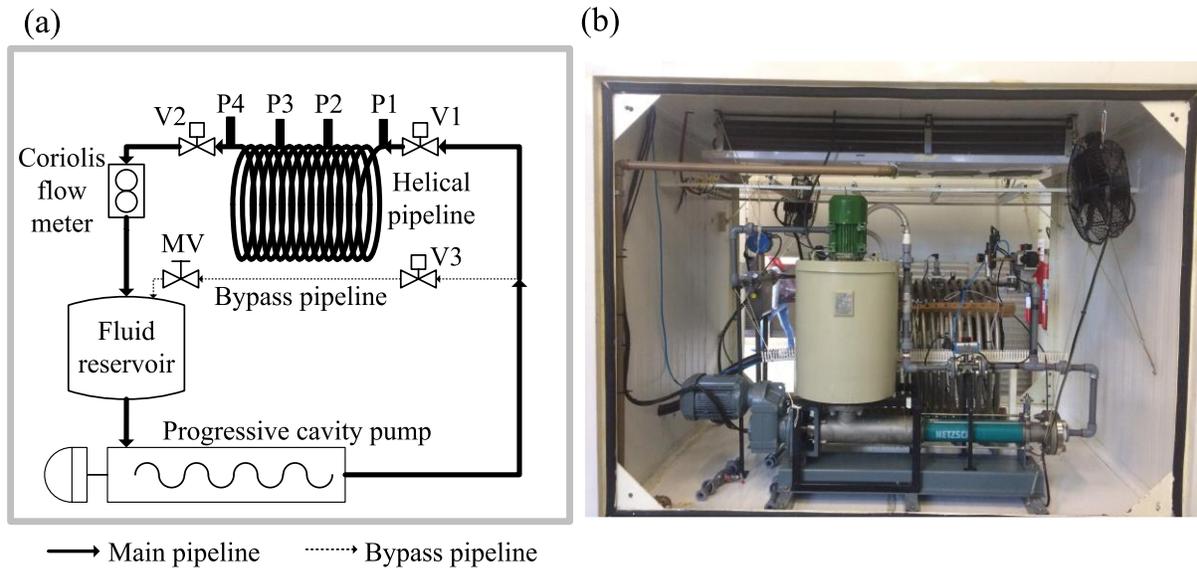


Figure 1. (a) Schematic and (b) photograph of the experimental setup.

The isolated chamber temperature was cooled by a vapor-compression refrigeration system, and heated by a set of electrical resistances. Temperatures were maintained between 5°C and 30°C automatically by a LabVIEW routine, based on the average readings of nine type-T thermocouples installed along the helical pipeline walls. During preliminary testing, the average of the measured temperatures varied approximately from 0.2°C after 90 min of stabilization. Fluid pressure, flow rates and the fluid temperatures during the experiments were measured and recorded in real time by the LabVIEW software. In addition, the software was used to control the pump and the fluid mixer. The pump flow rate was imposed by applying an electric current signal to a frequency inverter, which then altered the pump rotation proportionally to its operating range. The fluid mixer rotation could also be controlled in a similar manner. Finally, the LabVIEW software was also used to actuate the electro-pneumatic valves.

2.2. Description of the experiment

Due to the pump inertia, it was not possible to pressurize the fluid in the closed pipeline because pressures would rapidly increase to unsafe levels (greater than the maximum pump pressure 12 bar). Therefore, the procedure allowed fluid flow in the bypass while pressurizing the confined fluid inside the helical pipeline. Firstly, the inlet valve and bypass valve were opened and the outlet valve was closed, with the helical pipeline completely filled with fluid. Fluid temperatures were stabilized for 90 min. Then the pump was turned on, allowing flow through the bypass pipeline. Since the manual valve on the bypass restricted flow through the bypass, the fluid upstream to the bypass valve and the fluid inside the helical pipeline closed at the outlet was pressurized. Pressures are measured and recorded during the whole pressurization experiment. Moreover, according to Ghobadi and Muzychka (2005), fluid flow in a curved pipeline has a different behavior than flow in a straight pipe due to the presence of centrifugal forces, and this may influence pressure measurements. However, it assumed that the fluid remains stationary throughout the experiments as it is gradually pressurized with the pipeline outlet closed. Therefore, the influence of the pipeline geometry in the pressure measurements is considered to be negligible.

3. MATHEMATICAL MODEL

This section presents a summary of the mathematical model proposed by Oliveira and Negrão (2015) (Oliveira & Negrão, 2015). The geometry of the problem consisted of a straight pipeline of diameter D and length L in which a yield stress fluid is at rest. The initial pressure distribution was considered to be the same as the experiment, because

the yield stress fluid does not fully depressurize to zero due to the yield stress. Therefore, at $t = 0$ s, the initial values of P_1 , P_2 , P_3 and P_4 are 0.095, 0.526, 0.940 and 1.297 bar, respectively. It was assumed that the pipeline is non-deformable and symmetrical alongside the axis, and that there was no slip at the wall. The flow is assumed to be isothermal, compressible and one-dimensional. With these hypotheses, the mass balance and momentum equation are written, respectively, as:

$$\frac{\partial \rho}{\partial t} + \rho \frac{\partial V}{\partial z} + V \frac{\partial \rho}{\partial z} = 0 \quad (1)$$

$$\rho \frac{\partial V}{\partial t} + \rho V \frac{\partial V}{\partial z} = -\frac{\partial P}{\partial z} - \frac{4}{D} \tau_w \quad (2)$$

where ρ is the fluid density, V is the axial fluid velocity, P is the pressure, τ_w is the wall shear stress and t is the time variable and z is the axial coordinate. Isothermal compressibility is defined in function of the pressure wave speed c :

$$\alpha = \frac{1}{\rho} \left. \frac{\partial \rho}{\partial P} \right|_T = \frac{1}{\rho c^2} \quad (3)$$

where T is the fluid temperature. Combining the compressibility equation with the mass balance equation results in:

$$\frac{\partial \rho}{\partial t} + \frac{1}{\alpha} \frac{\partial V}{\partial z} + V \frac{\partial \rho}{\partial z} = 0 \quad (4)$$

which is the final form of the mass balance equation. The fluid used in the experiments is a Carbopol solution, which can be modeled by the Herschel-Bulkley constitutive equation for the fluid shear stress:

$$\begin{cases} \tau(\dot{\gamma}) = \tau_0 + k\dot{\gamma}^n, & \text{if } \tau > \tau_0 \\ \dot{\gamma} = 0, & \text{if } \tau \leq \tau_0 \end{cases} \quad (5)$$

where τ_0 is the yield stress, $\dot{\gamma}$ is the shear rate, k is the consistency index and n is the power-law index. The wall shear stress is then calculated in function of the shear rate, by substituting τ in the following equation:

$$\tau = \tau_w \frac{2r}{D} \quad (6)$$

Finally, τ_w can be substituted in the Equation (2). The partial differential equations (mass balance and momentum) are simplified to ordinary differential equations. Then, the problem is solved by the method of characteristics.

4. RESULTS AND DISCUSSION

4.1. Experimental verification of the pressure transmission in yield stress fluids

The working fluid was prepared using a mixture of 70% (mass percentage) of an ultrasonography Carbopol gel and 30% distilled water. Then, flow curve experiments were performed using a rotational rheometer, and the shear stress results were plotted as a function of the shear rate. The Herschel-Bulkley equation as fitted to these results to find out the fluid properties of yield stress, consistency index, power-law index. The data fit was performed from shear rates from 0.01 to 400 s^{-1} . The procedure is detailed in a paper to be submitted by Mitishita et al. (2017), which also presents a validation procedure for the experimental apparatus. The Carbopol fluid properties (yield stress,

consistency index, power-law index, density and pressure wave velocity) are presented in Table 1. The pressure wave velocity and density were assumed to be the same as water. The aforementioned experimental procedure was employed with water and Carbopol solution at 5°C, therefore only shows the fluid properties at this temperature. The results of the pressurization experiments with both fluids are shown in Figure 2.

Table 1. Carbopol solution properties: yield stress, consistency index, power-law index, density and pressure wave velocity).

T [°C]	τ_0 [Pa]	k [Pa.s ⁿ]	n [-]	ρ [kg/m ³]	c [m/s]
5	16.07	7.64	0.44	1000	1439

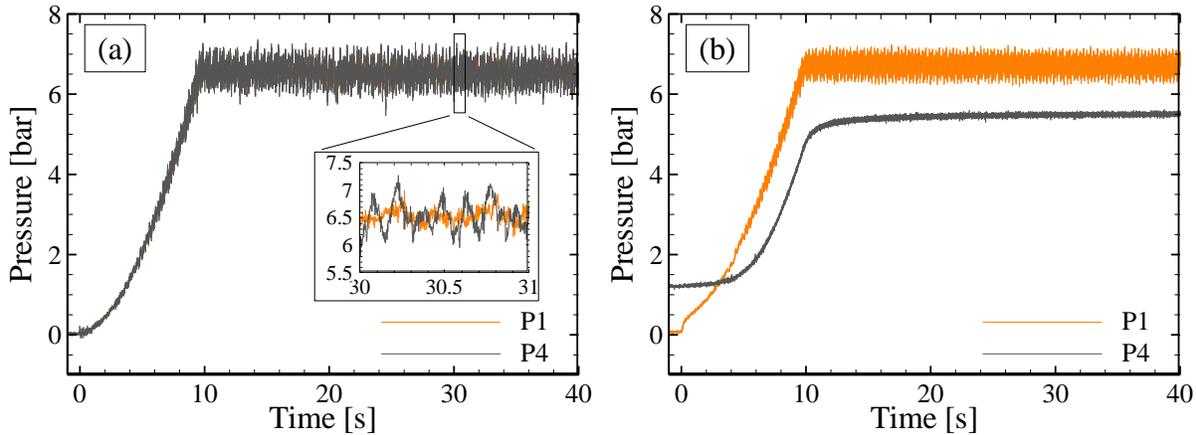


Figure 2. Pressure transmission test results for (a) water and (b) Carbopol solution at 5°C.

It can be seen from Figure 2a that the pressure imposed at the sensor P1 near the helical pipe inlet is fully transmitted to transmitter P4 near the closed outlet, as expected for Newtonian fluids according to Oliveira et al. (2012). However, concerning the viscoplastic Carbopol solution, it can be seen from Figure 2b that there is a pressure difference from P1 to P4. This corroborates the results from Oliveira et al. (2012) for a yield stress fluid. The pressure oscillations shown in both Figure 2a and Figure 2b are a result of the pulsations caused by the pump. The pump oscillations in water are more clearly seen because the pressure waves are able to travel through the entire pipeline length from P1 to P4 and reflect on the closed outlet valve. After the reflection, the wave amplitudes are doubled on the way back to the pipeline inlet at P1. In Figure 2b it is evident that the pump oscillations are greatly dissipated as they move from P1 to P4. This happens because of the high viscosity of the Carbopol solution.

4.2. Comparison to numerical simulation results

The experimental pressurization results were compared to numerical simulations with in the same conditions presented in Table 1. The helical pipeline was considered as a straight pipeline during the simulations, according to the hypothesis presented in Section 2. Additionally, the pipeline diameter and axial length were used as geometrical parameters. The experimental measurement of pressure at the inlet (P1) was used as a boundary condition (or BC), shown in Figure 3. The remaining boundary condition is simply a closed valve at the outlet, or a flow rate set to zero at the position of the outlet valve. Considering that the pressure curve from sensor P1 is a boundary condition, only the remaining pressure measurements P2, P3 and P4 are calculated by the algorithm.

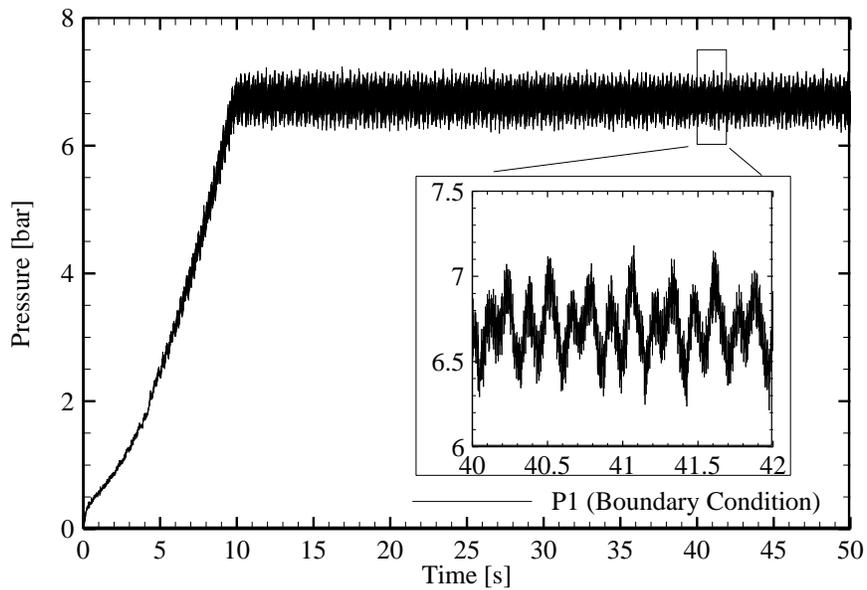


Figure 3. Inlet boundary condition for the simulation of the pressurization of the Carbopol solution up to approximately 6.8 bar at 5°C.

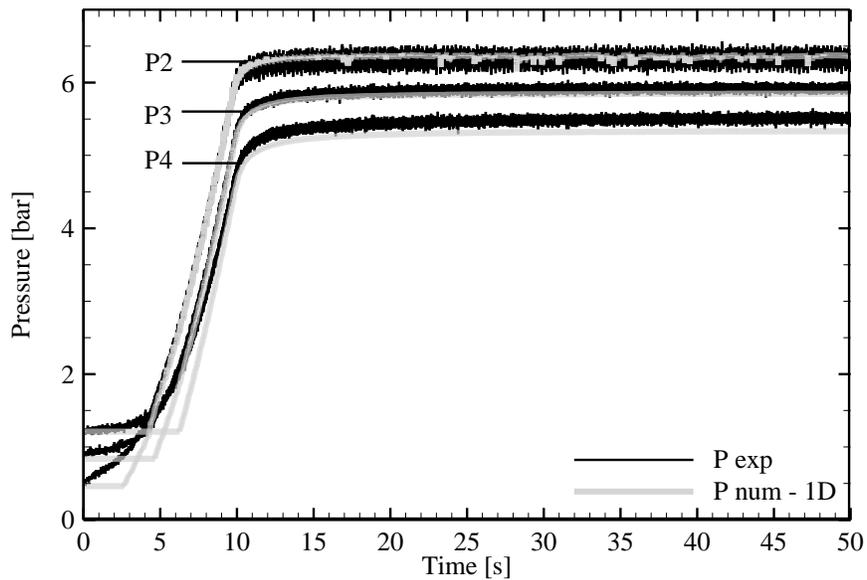


Figure 4. Comparison between experimental and numerical results of the Carbopol solution pressurization up to 6.8 bar at 5°C.

Figure 4 shows the comparison between measured and calculated pressures during the pressurization of the Carbopol solution as a function of time. During the transitory stage of the pressurization, between 0 and 10 s, the calculated pressure curves appear to be slightly delayed in comparison to the experiment. After steady state, the experimental and calculated pressures are very similar. Note that since the estimated and measured yield stress are different, the average numerical pressure gradient is larger. This is expected considering that the estimated yield stress would be larger than the real yield stress because of rheometer limitations and data fit errors. However, the

experimental and numerical results are still in good agreement, as the calculated steady-state pressures are within a 5% error band from the experimental results, as shown in Figure 5. This indicates that the mathematical model from Oliveira and Negrão (2015) can be employed to simulate the pressurization of a yield stress fluid in a pipeline closed at the outlet.

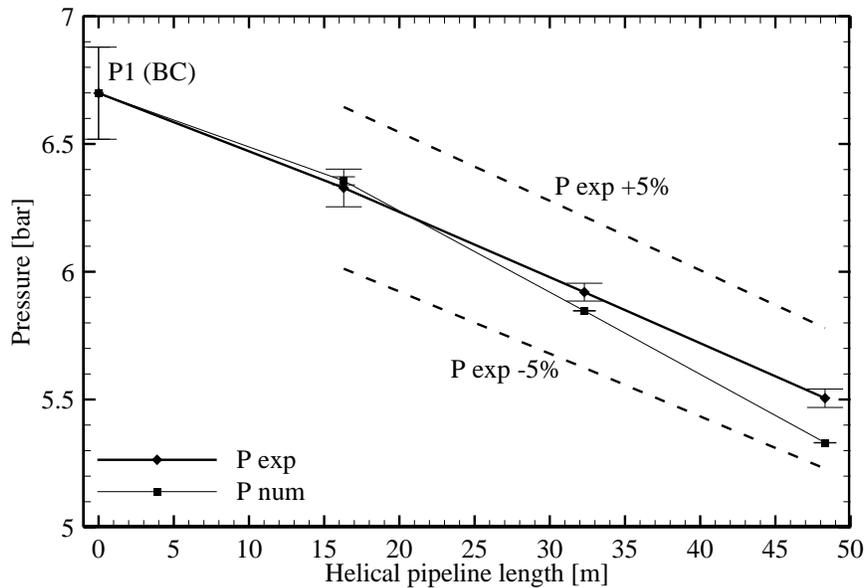


Figure 5. Comparison between the average steady-state experimental and numerical pressure distributions after the pressurization of the Carbopol solution to 6.8 bar at 5°C.

5. CONCLUSIONS

A comparison between an experimental and numerical analysis of the pressure propagation in viscoplastic fluids compressed in closed pipelines has been presented in this work. The test results with a Carbopol solution showed an attenuation in the applied pressure at the pipe inlet caused by the fluid yield stress. Therefore, the pressure distribution from P1 to P4 is non-uniform. Results from the pressurization of the Carbopol solution were then used to verify the simulation work based on the mathematical model proposed by Oliveira and Negrão (2015). The boundary conditions employed in the simulation work were the experimental pressure measurements at the inlet, and flow rate set to zero at the outlet. A significant delay in the calculated pressure curves were present in the transitory stage of the pressurization, when compared to the experiment. The numerical results were in a 5% error band when compared to the experimental pressure measurements at steady state. Therefore, the mathematical model is shown to be adequate to determine the final steady-state pressures after the pressurization of the Carbopol solution.

6. ACKNOWLEDGEMENTS

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