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Pressure transmission in yield stress fluids - An experimental analysis

Rodrigo S. Mitishita, Gabriel M. Oliveira, Tainan G.M. Santos, Cezar O.R. Negrão*

Federal University of Technology-Paraná – UTFPR, Academic Department of Mechanics – DAMEC, Post-graduate Program in Mechanical and Materials Engineering – PPGEM, Research Center for Rheology and Non-Newtonian Fluids – CERNN, Rua Deputado Heitor Alencar Furtado, 5000 - Bloco N - Ecoville - CEP 81280-340, Curitiba / PR - Brazil

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ABSTRACT

The current work presents an experimental investigation of the pressurization of a yield stress fluid contained in a closed pipeline under isothermal conditions. The tests were performed in a laboratory-scale flow loop placed inside a thermally controlled chamber. Sensors located along the pipeline measured fluid pressure and temperature. Differently from Newtonian fluids, experiments conducted with a viscoplastic fluid showed that the pressure imposed at one end of a closed pipeline was not fully transmitted to the other end, supporting prior mathematical model results. The results also revealed that the final pressure distribution was dependent not only on the fluid yield stress but also on the shear history the fluid underwent during pressurization and on the ratio between the pressure wave inertia and viscous dissipation. A comparison of the fluid yield stress obtained from rheometric measurements with the shear stress at the pipeline wall showed that they were of the same order of magnitude and that the higher the pressure wave inertia-viscous dissipation ratio the higher was the discrepancy between them.

1. Introduction

The always-increasing demand for energy and the reduction of oil reserves have motivated the oil industry to drill deeper and deeper wells. These very long wells can negatively affect the pressure propagation in drilling fluids, which is essential for well control operations, mainly under static conditions. For example, completion valves installed at the drillpipe end, near the well bottom, are hydraulically opened by pressurizing the fluid at the well surface. Engineers have argued that the pressure imposed at the surface is not fully transmitted to the valve position, preventing its operation. A possible solution for the problem is the substitution of the drilling fluid by a Newtonian fluid, usually water, which allows a complete pressure transmission from the surface to the valve. Nevertheless, this expensive and time-consuming solution should be avoided.

Drilling fluids are usually formulated as viscoplastic materials to inhibit flow below the fluid yield stress, precluding cuttings to drop to the well bottom under static conditions. On the other hand, some theoretical works in the literature [1,2] have demonstrated that the non-transmission of pressure is related to the fluid viscoplasticity. This pressure transmission problem in viscoplastic fluids confined in pipelines was firstly investigated mathematically by Oliveira *et al.* [1]. The authors showed that pressure was only transmitted in yield stress (or viscoplastic) materials if the shear stress at the pipeline wall, caused by pressure gradients, exceeded the fluid yield stress. The authors also concluded that the final pressure distribution along the pipeline was not only dependent on the fluid yield stress but also on the relation between the pressure wave inertia (product of fluid density and sound speed divided by pipe length) and the viscous dissipation (ratio of viscosity and square of pipe diameter). In another study developed by Oliveira *et al.* [2], they showed that the fluid compression rate could also affect the pressure propagation and consequently, the final pressure distribution along the pipeline.

A similar situation of pressure propagation takes place in the well-known water hammer problem that is caused by sudden valve closures during steady state flows in pipelines [3–5]. Despite this problem being extensively studied for many years, most publications have focused on Newtonian fluids [4,5]. Several authors [3,4,6–8] have proposed mathematical models to show the attenuation of pressure waves after a fast valve closure. Analogous to the pressure transmission problem in viscoplastic fluids, the pressure wave dissipation in water hammer is also dependent on the ratio between inertia and viscous forces. Differently from previous works, Wahba [9] and Oliveira *et al.* [10] studied the rapid valve closure in power law and Bingham fluid flows, respectively. While the first showed that the pressure wave attenuation increases with the power law index due to the higher viscous dissipation, the second verified a non-uniform pressure distribution along the pipeline after the complete pressure wave dissipation, similar to what was observed by [1] and [2]. Oliveira *et al.* [10] also demonstrated that the final pres-

* Corresponding author.
E-mail address: negrao@utfpr.edu.br (C.O.R. Negrão).

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sure distribution was influenced by inertia, viscous dissipation and the yield stress magnitude.

Additionally, pressure propagation in yield stress fluids during flow start-up has also been investigated mathematically by numerous authors [11–16]. While a constant pressure or flow rate is applied at the inlet during flow restarts, the outlet is open so that the fluid is displaced throughout the whole pipeline. Similar to what has been observed in problems where pressure is not transmitted, Negrão *et al.* [15] found out that the fluid flow did not start up if the pressure difference imposed to the pipeline was not enough to exceed the fluid yield stress.

Numerous experimental works have also been conducted to deal with flow start-up of yield stress fluids [17–19]. Their focus was mainly on measuring the required time for a Newtonian fluid to expulse a gelled waxy crude oil from the pipeline. El Gendy *et al.* [18] also verified that the flow only started up if the wall shear stress surpassed the fluid yield stress. Rønningsen [20] reported good agreement between values of shear stress and shear rates for waxy crude oils measured in a flow loop and in a controlled stress rheometer. The deviations ranged from 15% to 20%. Similarly, Lee *et al.* [21] corroborated the flow restart pressures of a waxy crude oil by comparing rheometric data with measurements obtained from an experimental apparatus.

Aqueous Carbopol solutions are commonly used as yield stress fluids in start-up experiments because they are transparent and also cheap and easy to formulate [22]. In spite of the slightly elastic behavior and weak thixotropy, Carbopol gels can be adequately described as a viscoplastic fluid [22,23]. Taghavi *et al.* [24], for instance, studied the displacement of a Carbopol solution by a Newtonian fluid and Alba *et al.* [25] extended the work of [24] for inclined pipelines. Sierra *et al.* [26] also evaluated the effect of the imposed pressure rate on the displacement of a Carbopol solution by a Newtonian fluid.

Despite the interest of the petroleum industry in the pressure transmission problem, there is yet a lack of experimental studies in the area. For instance, the works of [1,2] stated that the pressure transmission could be affected not only by the yield stress, but also by the pressure wave inertia and viscous dissipation. However, the only experimental investigation found in the open literature [2] was performed in a full-scale drilling rig in which the operation was quite complex, the process variables were difficult to control, such as the fluid properties and temperature, and the results were not quite repeatable, so that further investigation is still needed. In order to fulfill this absence of results, the current work puts forward an experimental investigation of the pressure transmission problem in a long closed pipeline containing a viscoplastic fluid. For that purpose, a laboratory-scale flow loop was built and was employed to conduct transient and steady state experiments using a Carbopol solution as the working fluid.

2. Experimental setup

A schematic representation and a photograph of the experimental apparatus are shown in Fig. 1. The experimental setup consisted of three main parts: hydraulic, temperature control and data acquisition systems. The hydraulic system installed inside a thermally isolated chamber was composed of a progressive cavity pump that sucked the working fluid from a 50 *l* storage tank (fluid reservoir) and delivered it either to a main pipeline that worked as the test section or to a bypass pipeline that prevented system overpressure. The pump operated within the pressure range of 0 to 12 *bar* and flow rates up to 0.37 *l*/s. The main pipeline was 48.3 *m* long, with an internal diameter of 20.45 *mm*, built in stainless steel and shaped in a helical form, while the bypass pipeline had an internal diameter of 13.8 *mm*. The helical diameter and pitch measured 727 *mm* and 52 *mm*, respectively. In order to homogenize the fluid mixture, a 1 *hp* electric agitator was installed on the top cover of the storage tank.

Four diaphragm pressure transducers, indicated by P_1 (inlet), P_2, P_3 and P_4 (outlet) in Fig. 1(a), were installed along the main pipeline walls to measure the fluid pressure inside the system. P_2 was located 16.3 *m* (L_1) away from P_1, P_3 was 16 *m* (L_2) from P_2 and P_4 was also 16 *m* (L_3) from P_3. These three lengths summed up the total axial pipeline length of 48.3 *m* ($L = L_1 + L_2 + L_3$). The $\frac{1}{2}$ inch diaphragms of the pressure transducers were positioned nearly coincident with the inner wall of the pipe so as to avoid any potential measurement errors due to yield stress effects. The pipeline was built in a helical shape to reduce the space occupied by the system while keeping a long circuit length. A volume of 50 *l* of fluid was added to the system, out of which 17.3 *l* filled up the flow loop and the remaining was stored in the tank. Three electro-pneumatic valves installed at the inlet and outlet of the helical pipeline, V_1 and V_2 respectively, and in the bypass, V_3, controlled the fluid flow through the hydraulic circuit. Fluid was displaced exclusively to the helical pipeline (full black lines in Fig. 1) when the inlet and outlet valves were opened and the bypass valve was closed and flowed only through the bypass (dashed lines in Fig. 1) when V_3 was opened and V_1 and V_2 were closed. A manual valve (MV) was also installed in the bypass pipeline downstream the automatic valve V_3. The purpose of this valve is explained in Section 3. A Coriolis flow meter, capable of measuring flow rates ranging from 0.015 to 1.53 *l*/s with 0.1 % uncertainty, was positioned downstream the outlet valve. This flow meter was also capable of measuring fluid density and temperature.

The chamber temperature was controlled within 5 and 30°*C* by using a LabVIEW routine that actuated a refrigeration system and an electric heater. The controlled temperature was based on the average readings of eight type-T thermocouples installed along the helical pipeline walls. The oscillations of the controlled temperature during the experiments were not larger than ± 0.2 °*C*. The data acquisition-control system was responsible for measuring pressure, flow rates and fluid temperatures, for actuating the electro-pneumatic valves and for controlling the pump and the fluid mixer speeds. Fast pressure transients were detected by four pressure transducers with measuring range of 0 to 16 *bar*, accuracy of 0.1 % of the span, and frequency of 500 *Hz*. The pump speed was controlled from 0 to 105 *rpm* by a frequency inverter.

3. Experimental procedure

The following steps describe the experimental protocol used for the pressure transmission experiments:

- The chamber temperature was firstly controlled at the desired value during 90 minutes.
- After the temperature stabilization, the inlet valve (V_1), the bypass valve (V_3) and the manual bypass valve (initially completely open) were opened and the outlet valve (V_2) was maintained closed.
- The tests were initiated by starting the data acquisition routine and 15 *s* later the pump was turned on to a desired flow rate. While the fluid flowed through the bypass, the pressure was increased within the main pipeline. Due to inertia, the pump rotor did not reach a constant speed instantaneously, and consequently the fluid was gradually pressurized to the desired final pressure. To further pressurize the fluid in the main pipeline, the manual bypass valve (MV) was partially closed to restrict fluid flow in the bypass.
- The pump was turned off after 90 *s* and the data acquisition was disabled after 150 *s*, ending the experiment.

It is worth mentioning that the system main control variable was the fluid pressure that depended not only on the flow rate controlled by the pump speed but also on the opening of the bypass manual valve. The experimental procedure in each condition was performed three times to assure repeatability and the measurements were carried out at 5 and 25°*C* to evaluate the temperature effect on the results.

4. Preliminary tests

For the sake of comparison, pressure transmission experiments were firstly conducted with a Newtonian fluid and the results are discussed in Section 4.1. A summary of the test preparation and rheology of the

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