APPARENT WALL SLIP IN FLOWS OF VISCOPLASTIC FLUID THROUGH A PARALLEL-PLATE CHANNEL

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Abstract *The present research consists of an experimental study of the behavior of aqueous Carbopol dispersions and the phenomenon of apparent wall slip during an internal flow through a parallel-plate channel. The channel is 100mm wide, 150mm long, and the gap between plates is 1mm. We use plates of different materials and roughnesses. The Reynolds number is low for all cases investigated to ensure negligible development length. In the experiments, the pressure drop is measured for different flow rate values and the results are presented in the form of curves of dimensionless average velocity versus dimensionless wall shear stress. We also performed experiments with glycerol, and the results agreed with the analytical solution available in the literature. Moreover, this agreement ensures the absence of apparent wall slip for this Newtonian case.*

Keywords: *Apparent wall slip; Drag reduction; Coating; Wetability*

1. INTRODUCTION

Due to it's numerous proved reserves, heavy oils have a major importance in the world's economic scenario. These oils are abundant in Brazil, and to optimize the cost-benefit of the extraction and transportation of these materials, it is important to understand the oil flow properties. Since the extracted oils are highly viscous, it is necessary to have high pumping power, which represents a big expense to the companies.

Heavy oils can behave as viscoplastic fluids. Such materials present a yield stress, meaning that flow will occur only in case a minimum shear stress is applied (Barnes (1999); Hartnett and Hu (1989)). Moreover, under some certain internal-flow conditions, i.e. at low shear rates, apparent wall slip may be observed (Fig. 1). This phenomenon consists of the particles moving away from the solid surfaces, leaving a thin layer of the continuous phase of a lower viscosity liquid near the surface. This low-viscous layer acts as a lubricant (Barnes (1995)).

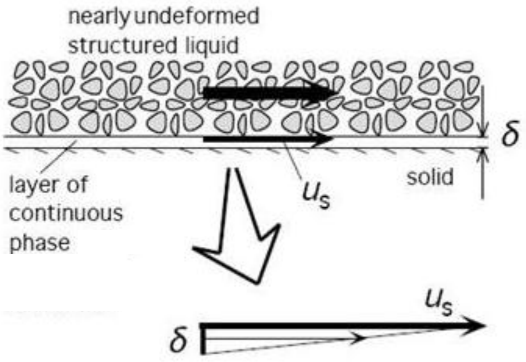


Figure 1. Apparent wall slip scheme.

Apparent wall slip has the potential of reducing the head loss of oil transportation and also of facilitating the flow, reducing the energy consumption of the pumping process, resulting in a low-cost transportation method. Experimental evidences indicate that the intensity of this wall slip is dependent on two main properties of the internal surface of the pipe: roughness and wetability.

Hence, the goal of this research is to study the wall slip effect in flows of viscoplastic materials, observing the flow's behavior with different surfaces and fluids. With the experimental results it is expected to observe relation between them, studying the dependence of the apparent wall slip with surface roughness and wetability.

2. EXPERIMENT

The experimental apparatus (Figs. 2 and 3) consists of a test section (parallel plates), a reservoir, which is connected to a progressive cavity pump that pumps the fluid into the test section, and a digital manometer connected to the experiment, to measure the pressure drop.

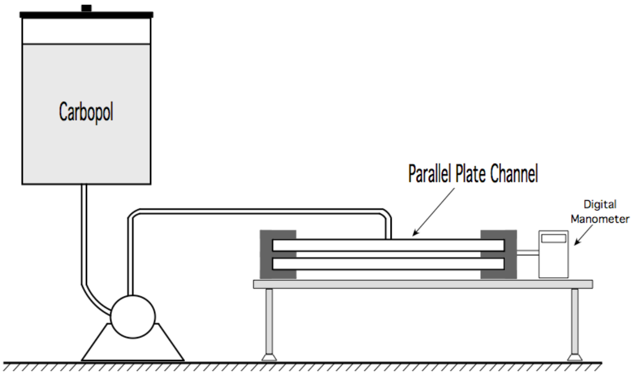


Figure 2. The section's schematic layout.

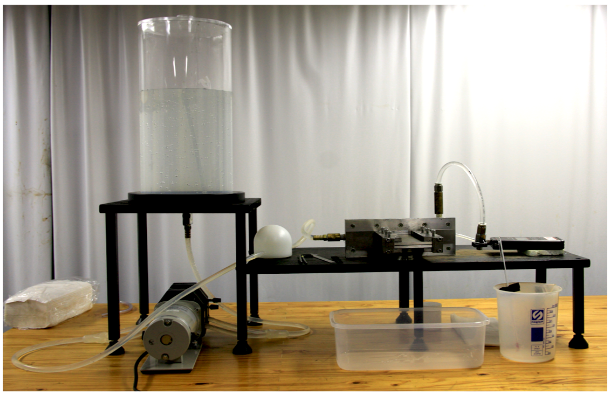


Figure 3. Actual experimental section.

The test section consists of two plates of 100mm width, 150mm length and thickness between 4mm and 6mm, as can be seen in Figs. 4 and 5. The gap between the plates is equal to 1.00mm - plates are always separated by 1.00mm thick stainless steel strip so the flow area is constant. There are four pairs of stainless steel plates, a pair of glass plates and a pair of Teflon plates. The main idea is to vary the wetability and roughness independently.

The fluid is pumped from the reservoir through the plates into a recipient until it reaches steady flow. Then, a new recipient with a thermometer in it is placed under the plate's end and a chronometer is started. After a certain time the chronometer is stopped and the collected mass of fluid is weighted. The average pressure, the duration of the flow, the collected mass and the temperature are used to calculate the mass flow rate $\dot{Q}$ and to further evaluate the results. The temperature is used to control the conditions under which the experiment is performed, as well as to estimate the viscosity of the fluid.

The test is repeated at least five times for each pair of plates and for different flow rate values, determining the conditions under which the phenomenon of wall slip occurs. The final results are presented in curves of dimensionless average velocity versus dimensionless shear stress.

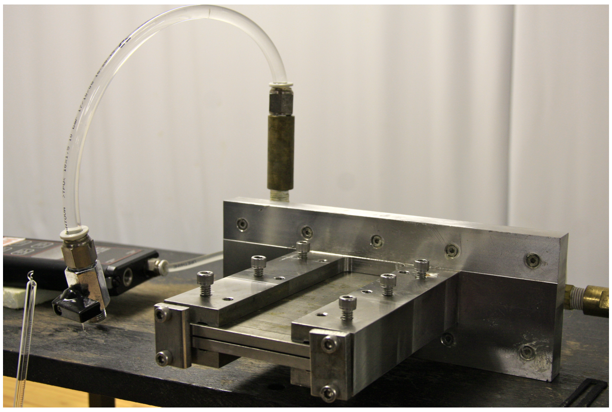


Figure 4. Parallel plate channel.

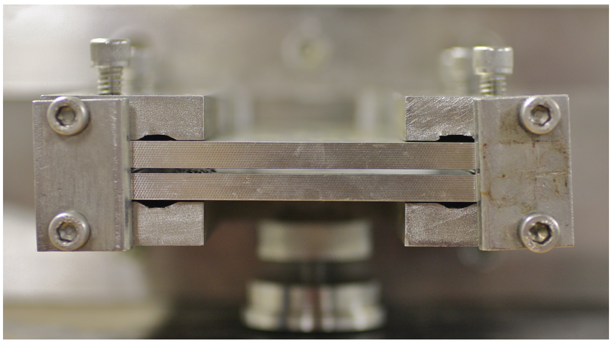


Figure 5. Front view of the parallel plate channel.

For the validation of the experiment we use a glycerol solution (90% glycerol and 10% water) as our Newtonian fluid. A 0.1% Carbopol dispersion is used as our non-Newtonian fluid. Carbopol dispersions are great model fluids for viscoplastic materials. Its main advantages are the easiness with which it is possible to control its yield stress and viscosity - only by varying its concentration, lack of toxicity, and its transparency. Another advantage of using of Carbopol in experiments is that its flow properties are practically temperature independent. A rotational rheometer AR-G2 is used to obtain the viscosity function of the Carbopol dispersion. The cross hatched parallel plates geometry is used to avoid apparent wall slip in the rheometric measurements, as discussed below (Sec. 4.2.1).

3. MATHEMATICAL FORMULATION

The flow of a Newtonian fluid in a parallel plate channel, as shown in Fig. 6, can be calculated through the Navier-Stokes equations.

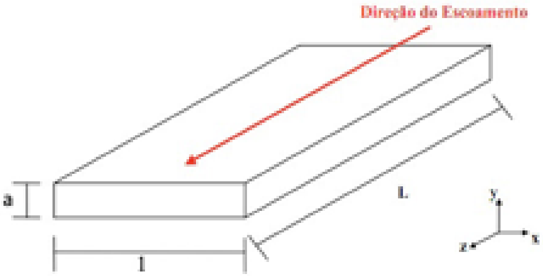


Figure 6. Scheme of the parallel plate channel.

Using the appropriate hypothesis, e.g. fully developed flow (velocity is constant in the z-direction), since the gap a is much smaller than the other dimensions l and L, and no-slip condition (velocity u equal to zero on both surfaces), the following equation for the velocity profile can be obtained:

$$u = \frac{a^2}{2\mu}\left(\frac{\partial p}{\partial z}\right)\left[\left(\frac{y}{a}\right)^2 - \left(\frac{y}{a}\right)\right] \tag{1}$$

To obtain the volumetric flow rate the velocity profile must be integrated as follows:

$$Q = \int_A \vec{V} d\vec{A} = \int_0^a \frac{l}{2\mu}\left(\frac{\partial p}{\partial z}\right)\left(y^2 - ay\right) dy = \frac{a^3 l}{12\mu}\left(\frac{\partial p}{\partial z}\right) \tag{2}$$

or simply:

$$Q = \frac{a^3 l}{12\mu L}\Delta P \tag{3}$$

where Q is the volumetric flow rate, μ is the viscosity of the fluid at a given temperature, Δ P is the pressure drop across the section, and a, l and L are, respectively, the length, width and gap of the channel, also shown in Fig. 6.

In the case of non-Newtonian fluids, instead of having a constant value for viscosity μ, a viscosity function η (t , $\dot{\gamma}$) is needed. Moreover, the velocity profile will also be different.

4. RESULTS

4.1 Newtonian case

Initially, tests were performed using a glycerol solution (90% glycerol + 10% water) to validate the test section according to the mathematical formulation. Since the viscosity of glycerol varies strongly with temperature, it is important to control the experiment temperature. Table 1 presents fluid properties, namely viscosity (μ) and specific mass (ρ), and its dependence on temperature:

Table 1. Properties of glycerol solution for different temperatures.

	18°C	19°C	20°C	21°C	22°C	23°C	24°C
μ (Pa.s)	0.2073	0.1920	0.1775	0.1732	0.1686	0.1561	0.1445
ρ (kg/m^3)	1232.3	1230.9	1229.9	1230.9	1231.7	1230.1	1229.5

The validation of the experiment consists of comparing the measured mass flow rate $\dot{Q}$ written as volumetric flow rate

$$Q_{exp} = \frac{\dot{Q}}{\rho} \tag{4}$$

with the flow rate calculated using the pressure drop (ΔP) measured:

$$Q_{theor} = \frac{a^3 l}{12\mu L}\Delta P \tag{5}$$

The results for Q_{exp} and Q_{theor} are presented in Tab. 2 together with the percentile difference between both flow rates:

Table 2. Results for newtonian fluid (90% glycerol + 10% water).

Nominal Q	Q_{theor} (m^3/s)	Q_{exp} (m^3/s)	Difference (%)
1	$8.81\text{x}10^{-7}$	$9.22\text{x}10^{-7}$	4.60
2	$2.27\text{x}10^{-6}$	$2.10\text{x}10^{-6}$	7.35
3	$3.64\text{x}10^{-6}$	$3.46\text{x}10^{-6}$	4.86
4	$5.10\text{x}10^{-6}$	$4.88\text{x}10^{-6}$	4.35
5	$5.94\text{x}10^{-6}$	$5.77\text{x}10^{-6}$	2.81

Plotting the results in terms of Qμ and ΔP displays a linear relationship, since the slope of the curve depends only upon geometric parameters (a, l, and L). The curve is shown below (Fig. 7):

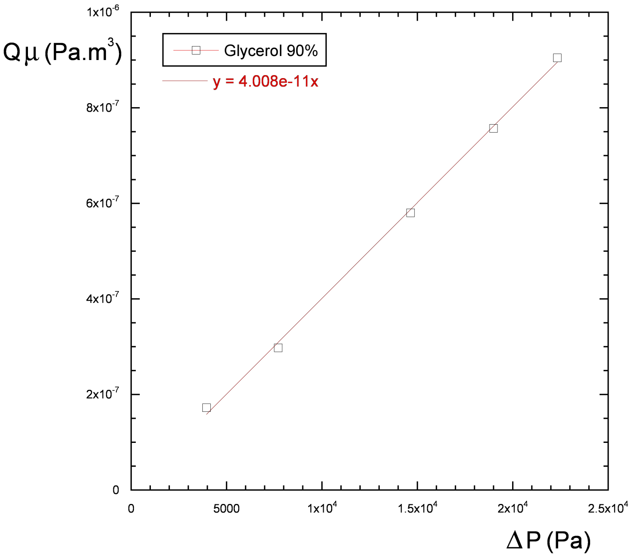


Figure 7. Validation using Newtonian fluid.

4.2 Non-Newtonian case

4.2.1 Rheology

It is known that the viscosity of non-Newtonian fluids depends not only on temperature, but also on shear rate and time. Hence, it is important to obtain a flow curve, in which the viscosity dependence with the shear rate can be evaluated for a fixed temperature and steady-state condition, i.e. independent of time. Apparent wall slip may also be present in rheometric experiments. According to Barnes (2000); Roberts and Barnes (2001) there are two ways to deal with this source of measurement error: i) to use roughened or chemical altered surfaces or ii) to vary the gap and then extrapolate the results for a very large gap.

The influence of geometry on the results for the 0.1% Carbopol dispersion was investigated. Smooth parallel plates were used with different gaps and compared with roughened (*cross hatched*) parallel plates. The results are shown in Fig. 8 of a flow curve performed at 25°C:

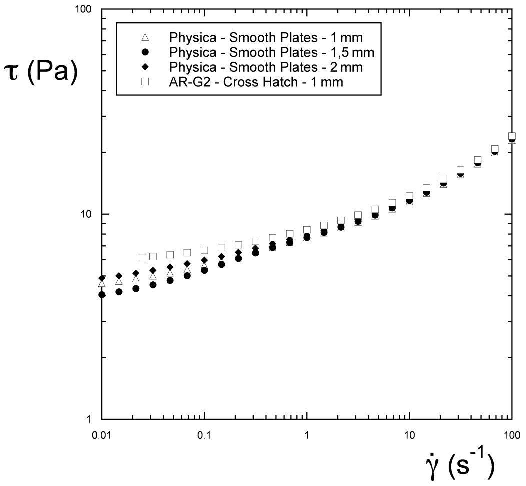
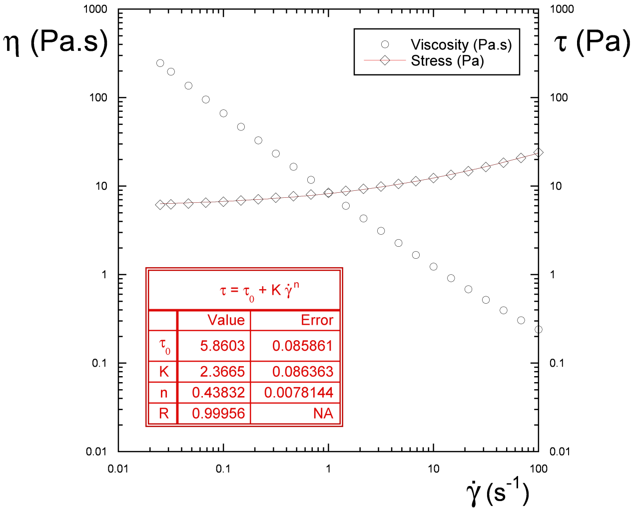


Figure 8. Flow curve of Carbopol 0.1%: apparent wall slip.

Comparing the results for smooth plates it is noticeable that increasing the gap diminishes the slip, as expected. However, for this material, increasing the gap is not sufficient to eliminate apparent wall slip. It can be seen that the cross hatch geometry provides the best results when compared to smooth plates. Hence, we rely on the cross hatch geometry curve to obtain the viscosity of the Carbopol dispersion. A curve fitting with the Herschel-Bulkley model is given in Fig. 9:



$\tau = \tau_0 + K\,\dot{\gamma}^n$

	Value	Error
τ_0	5.8603	0.085861
K	2.3665	0.086363
n	0.43832	0.0078144
R	0.99956	NA

Figure 9. Curve fitting with the Herschel-Bulkley model.

4.2.2 Preliminary experimental results

When apparent wall slip is present it is expected that the flow rate measured in the experiment will be higher for the smooth surfaces when compared to the roughened plates. Preliminary experimental data with 0.1% Carbopol dispersion is presented in Tab. 3 for three different nominal flow rates:

Table 3. Experimental results for Carbopol 0.1% .

Nominal Q	Type of surface	Q_{exp} (m^3/s)	Difference (%)
1	Smooth	$4.98\text{x}10^{-6}$	
1	Roughened	$3.70\text{x}10^{-6}$	25.76
2	Smooth	9.2010^{-6}	
2	Roughened	$8.85\text{x}10^{-6}$	3.88
3	Smooth	$1.11\text{x}10^{-5}$	
3	Roughened	$1.06\text{x}10^{-5}$	4.73

From the results it is possible to observe that Q is considerably higher for the smooth plates only for the lowest nominal flow rate of “1" (25% difference between both experiments). For the nominal flow rate of 2 and 3 the flow rates measured using smooth or roughened surfaces are approximately the same (difference < 10%). This is readily explained by the fact that apparent wall slip occurs at low shear rates. Probably, for this concentration of the Carbopol dispersion, low shear rates are generated only by the smallest flow rate imposed by the pump.

5. FINAL REMARKS

The experimental setup was successfully built. The test section was validated using a Newtonian fluid. Apparent wall slip was identified in the rheometric tests of the Carbopol dispersion and subsequently avoided by performing the rheological tests with cross hatched parallel plates. Preliminary results using non-Newtonian fluid were also presented.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Barnes, H.A., 1995. “A review of the slip (wall depletion) of polymer solutions, emulsions and particle suspensions in viscometers: its cause, character, and cure”. *J. Non-Newtonian Fluid Mech.*, Vol. 56, pp. 221–251.

Barnes, H.A., 1999. “The yield stress — everything flows?” *J. Non-Newtonian Fluid Mech.*, Vol. 81, pp. 133–178.

Barnes, H.A., 2000. “Measuring the viscosity of large-particle (and flocculated) suspensions — a note on the necessary gap size of rotational viscometers”. *J. Non-Newtonian Fluid Mech.*, Vol. 94, pp. 213–217.

Hartnett, J. and Hu, R., 1989. “The yield stress - an engineering reality”. *Journal of Rheology*, Vol. 33, No. 4, pp. 671–679.

Roberts, G.P. and Barnes, H.A., 2001. “New measurements of the flow-curves for carbopol dispersions without slip artefacts”. *Rheol. Acta*, Vol. 40, pp. 499–503.

8. RESPONSIBILITY NOTICE