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BEHAVIOR OF NEWTONIAN AND NON-NEWTONIAN FLUIDS IN PUMPING AND TRANSPORT PROCESSES

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ABSTRACT. The present study investigates the behavior of Newtonian and non-Newtonian fluids in pumping and transport processes, using a laboratory facility. The rheological behavior of the selected fluids were determined by a rotational viscometer with concentric cylinders. The effect of pressure difference on pumping of selected fluids in the laboratory circuit showed a linear decrease of effective/delivered volumetric flow rate for the Newtonian fluid, glycerin/water 80%, and a non-linear decrease for non-Newtonian fluid, Separan AP 30E, 2g/l.

Keywords: *Newtonian, non-Newtonian fluids, apparent viscosity, material consistency, flow behavior index, volumetric flow rate, pressure difference, pumping and transport.*

INTRODUCTION

Fluid flow in pipelines and pumps is a fundamental topic and a crucial aspect of practical engineering that can affect a broad range of operations in industries such as chemical, pharmaceutical, food and agriculture, oil and gas [1-4]. The correlation between rheological properties, flow rate and pump selection, based on modelling, simulation and experimental validation, can be challenging for ensuring efficient transport, especially for fluids with non-Newtonian behavior [5-8].

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The fluids used in the present application have Newtonian or non-Newtonian behavior, shear-thinning or pseudoplastic behavior, each exhibiting distinct flow properties [9]. Newtonian fluids, such as water, or simple liquids such as alcohol, gasoline, diesel or mineral oils, under low to moderate flow rates, have a constant viscosity regardless of the applied rheological parameters, shear stress, τ, or the shear rate, $\dot{\gamma}$. With a linear relationship between these two parameters, the flow behavior is predictable, and engineers can easily calculate flow rates and pressures.

The study of Newtonian fluids is foundational in fluid mechanics, and it is a pivot when compared to non-Newtonian fluids [10].

Described by Isaac Newton's law of viscosity around 1687, the equation (1) is still groundbreaking and establishes the fundamental proportional relationship between shear stress and shear rate.

$$\tau = \eta \cdot \dot{\gamma} \tag{1}$$

where: τ is the shear stress, force per unit area exerted by the fluid (Pa), η - the dynamic viscosity, the constant value for Newtonian fluids at constant thermodynamic conditions (Pa·s), $\dot{\gamma}$ - the shear rate, rate at which the fluid layers move relatively to each other (1/s).

Non-Newtonian fluids are fluids whose viscosity changes with the rheological parameters shear rate, or shear stress, meaning their behavior is not anymore constant [9, 10]. Shear-thinning fluid are non-Newtonian fluids that exhibit a decrease in viscosity as the shear rate increases. This means that when these fluids are subjected to stress or deformation, they become less viscous, making them easier to flow. Examples of materials that exhibit shear-thinning behaviors are blood, paints and coatings, ketchup, polymer melts or gels, lotions and creams, muds and slurries.

The flow behavior of shear-thinning fluids is essential in medicine for designing specific medical devices like blood pumps, industrial and agricultural manufacturing, oil and gas field or wastewater management for choose pumps and pipes. The non-Newtonian behavior adds a layer of complexity to fluid dynamics and necessitates models that are more sophisticated to predict flow properties.

The power law model, also known as the Ostwald-de Waele model, equation (2), was first proposed by Ostwald in the late 19^{th} century (around 1895) and later refined by de Waele in the early 20^{th} century (around 1923) and describes the non-linear relationship between shear stress, τ, and the shear rate, $\dot{\gamma}$.

$$\tau = K \cdot \dot{\gamma}^{n} \tag{2}$$

where: τ is the shear stress (Pa), $\dot{\gamma}$ - the shear rate (1/s), K – material consistency, a material constant that indicates the fluid's flow resistance (Pa·s^n), and n – flow behavior index (-), with the value: n < 1 for shear-thinning or pseudoplastic fluids, n = 1 for Newtonian fluids, and n > 1 for shear-thickening or dilatant fluids.

The Hagen-Poiseuille equation (3) describes the flow of an incompressible, Newtonian fluid through a uniform cross-section along its length, under laminar flow conditions, when the fluid moves in parallel layers [10]. This equation is essential to understand the relationship between pressure drop, volumetric flow rate, the proprieties of the fluid and dimensions of the flow system.

$$Gv = \frac{\pi \Delta P r^4}{8\eta L} \tag{3}$$

where: Gv is the volumetric flow rate, the volume of fluid passing through the pipe per unit of time (m^3/s), ΔP - the pressure drop, the difference in pressure between inlet and outlet in the pipe (Pa), r - the radius of the pipe (m), η - the dynamic viscosity of the Newtonian fluid (Pa·s), L - the length of the pipe (m).

For shear-thinning fluids, the effective viscosity or apparent viscosity is a function of the shear rate, equation (4), and the volumetric flow rate becomes as equation (5) shows [9]:

$$\eta_{eff} = K \cdot \dot{\gamma}^{n-1} \tag{4}$$

$$Gv = \frac{\pi \Delta P r^4}{8\eta_{eff} L} \tag{5}$$

The objective of the present study was to determine experimentally and understand how two fluids, one Newtonian and the other non-Newtonian, behave under various conditions at pumping and transport. The knowledge of non-Newtonian fluid effects on the pump performance is fundamental in the design process, as well as in the pump choice. In addition, it has significant implications in control of industrial processes, reducing energy consumption, and improving the efficiency of fluid transport and pumping systems.

RESULTS AND DISCUSSION

a. Rheological behavior

The rheological behavior of the chosen samples, glycerin/water mixture as Newtonian fluid and Separan AP 30E as non-Newtonian fluid, evaluated by the viscosity curves, are shown in Figure 1 and 2.

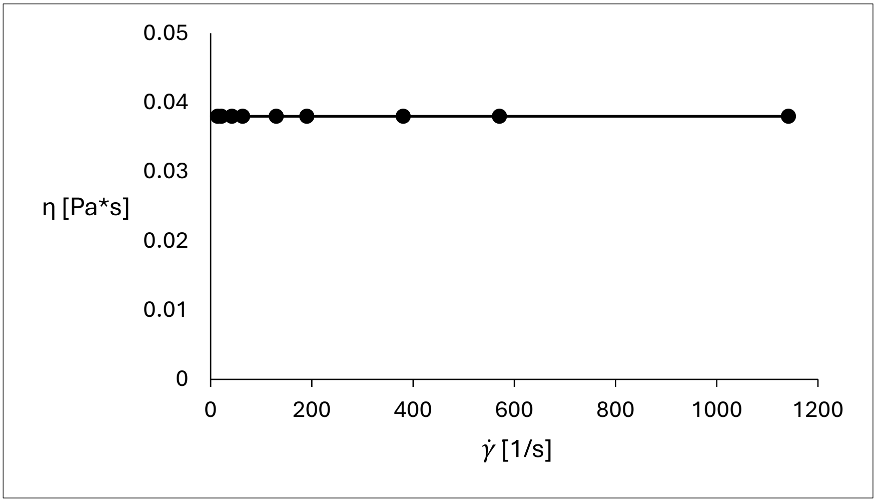

Figure 1. Viscosity curve for the Newtonian fluid: glycerin/water (80 %, vol. %)

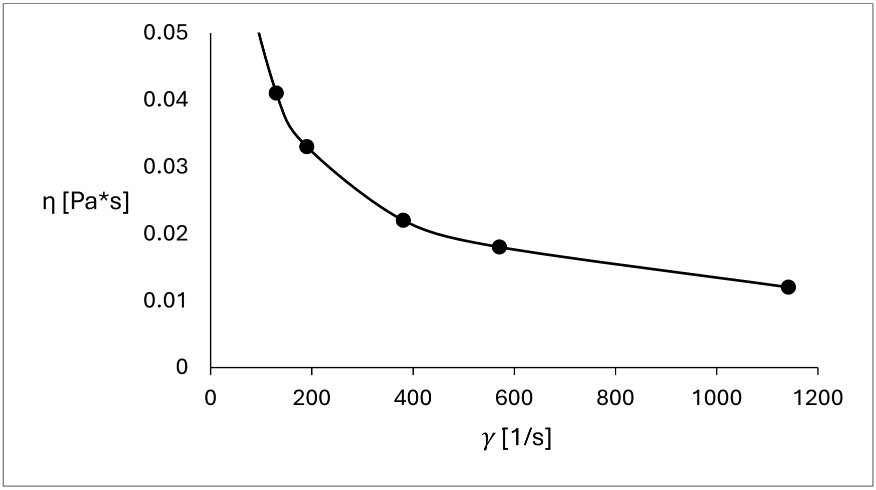

Figure 2. Viscosity curve for the shear-thinning/pseudoplastic solution: Separan AP 30E (2g/l H_2O, 25°C)

The effective viscosity was obtained in accordance with Newton's law, from the ratio between shear stress and shear rate. To determine the material consistency, K, and the flow index, n, the shear stress against shear rate in double logarithmic scale is presented in Figure 3 for Separan sample.

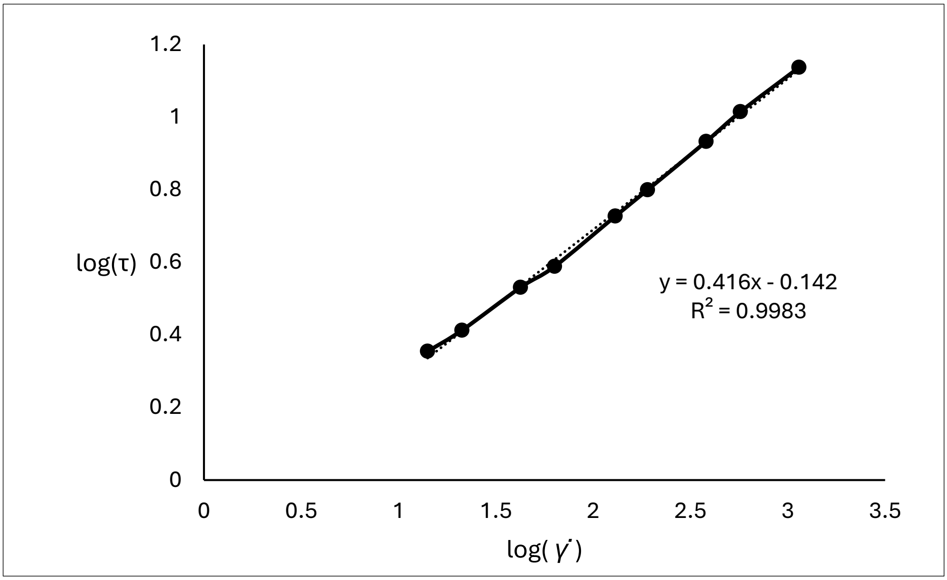

Figure 3. Flow curve in logarithmic scale for the pseudoplastic liquid: Separan AP 30E (2g/l H_2O, 25°C)

The constant viscosity value of 0.038 Pa·s, and the obtained value of flow index, n = 1, for glycerin/water mixture confirms the Newtonian behavior.

In the case of Separan AP 30E, the apparent viscosity decreases with the increase of shear rate, and flow behavior index lower than 1, n = 0.416, confirms the shear-thinning or pseudoplastic behavior. The material consistency in this case is K = 0.721 $Pa \cdot s^n$.

b. Pumping behavior

Figures 4 and 5 show the effective volumetric flow of glycerin/water and Separan AP 30E as a function of pressure difference between delivery and suction, with the change of the pump's rotation speed.

The obtained curves show a linear decrease of the volumetric flow with the increase of pressure difference in pump for the glycerin/water mixture, a Newtonian fluid, and a non-linear decrease for Separan AP 30E, a shear-thinning fluid.

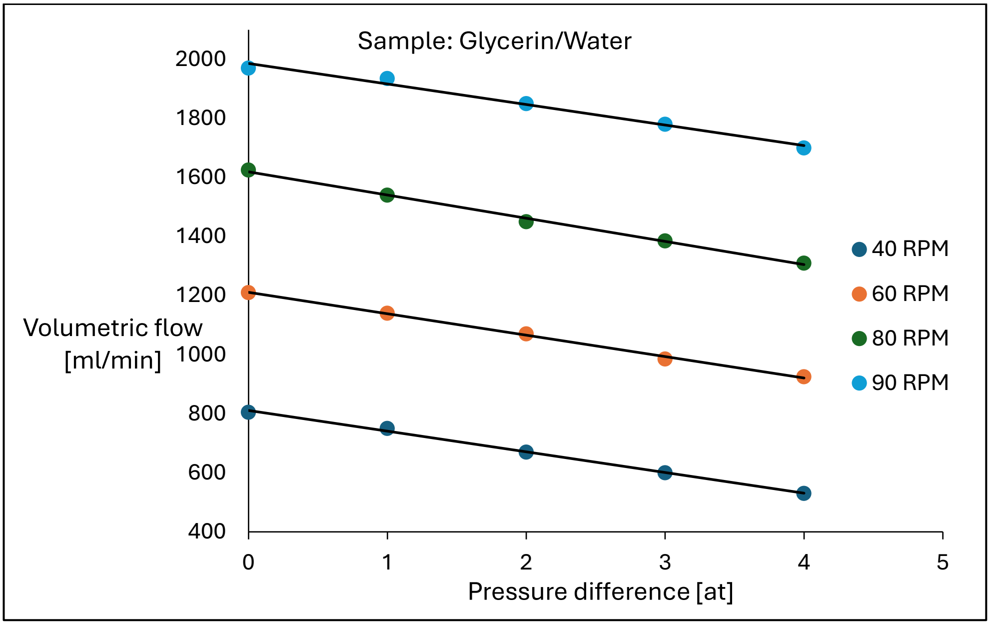

Figure 4. Volumetric flow rate vs. pump's pressure difference for glycerin/water

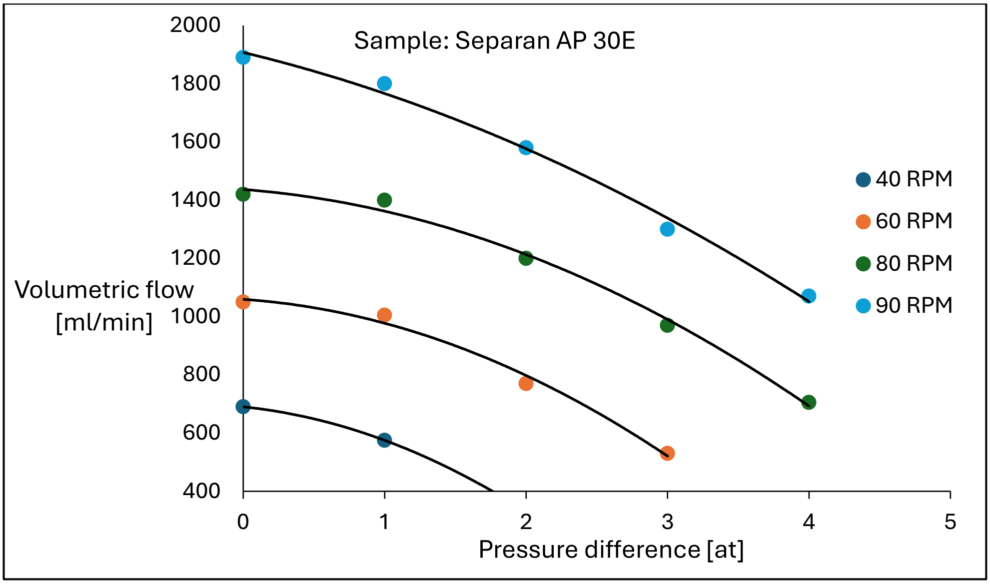

Figure 5. Volumetric flow rate vs. pump's pressure difference for Separan AP 30E solution

In order to explain the decrease of the effective volumetric flow, G_{Veff}, we have to consider that the effective volumetric flow or outflow is the difference between theoretical volumetric flow, G_{Vt}, and the recirculation flow, G_{Vr}, which is proportional with the friction/drop pressure, equation (6).

Thus, increasing the pressure difference, the recirculation flow in the system increases and as result, the value of effective/delivered volumetric flow of the pump will decrease. The friction losses in the system increases also due to the decrease of the effective viscosity, for the non-Newtonian fluid, as equation (7) shows.

$$Gv_{eff} = Gv_t - Gv_r \qquad (6)$$

$$Gv_r = C \times \frac{\Delta P}{\eta_{eff}} \qquad (7)$$

The constant *C* contains the numerical constants and the dimensions that characterize the pipeline; ΔP is the pressure drop in the pipeline; n is the flow behavior index. For the viscosity, the effective viscosity or apparent viscosity, corresponding to the respective shear rate must be set.

The results show that the influence of the recirculation is more evident for non-Newtonian fluids than for Newtonian fluids, the effective flow rate decrease is higher for Separan solution comparative with glycerin/water mixture.

Figure 6 shows the influence of rotation speed on the effective volumetric flow rate at different pressure. In the domain of rotation speed used in the present study, the volumetric flow rate increases linearly with the rotation speed at the same pressure difference for both fluids.

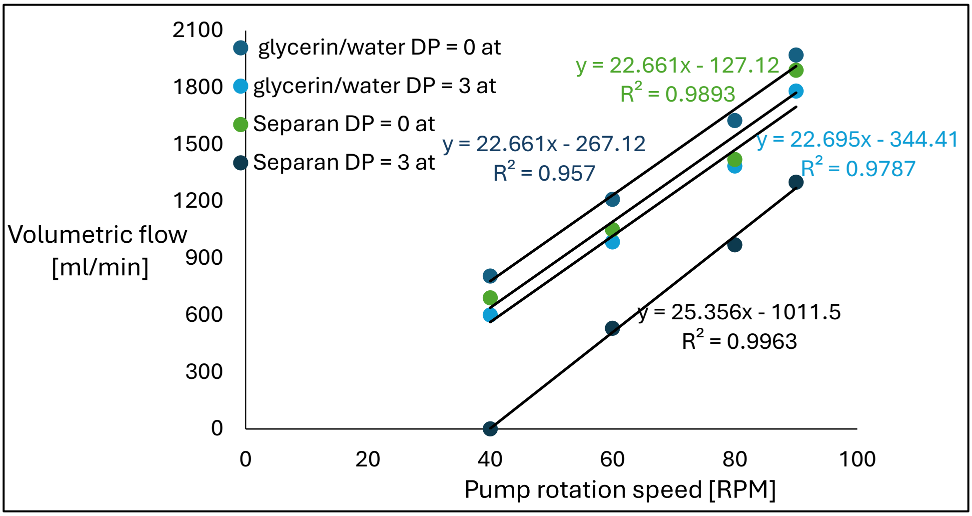

Figure 6. Volumetric flow rate vs. pump's rotation speed for glycerin/water mixture and Separan AP 30E at pressure difference 0 and 3 at

The slope of the linear curves has almost the same value, around 22, for the glycerin/water mixture, a fluid with constant viscosity, but a higher value, around 25, in the case of Separan at higher pressure difference. The result can be explained considering that the decrease of effective/ apparent viscosity is more significant at higher applied shear load.

CONCLUSIONS

The study explores the influence of the rotation speed and pressure difference as operational parameters on the pumping and transport of Newtonian and non-Newtonian fluids.

The rheological behavior of glycerine/water as Newtonian fluid and Separan AP 30E as shear-thinning fluid was experimentally determined using a rotational viscometer with two concentrically cylinders.

The effective delivered volumetric flow rate decreased with the pump's pressure difference in accordance with equation (6), the decrease was more obvious for Separan solution than for the glycerin/water mixture.

In the domain of rotation speed used in the present study, the volumetric flow rate increases linearly with the rotation speed at the same pressure difference, for both Newtonian and non-Newtonian fluids.

EXPERIMENTAL SECTION

In this section, there are described the materials, methods, and procedures used for the transport and pumping of the two fluids with different rheological behavior.

Materials: Glycerine/water mixture, 80 vol. % glycerin, as Newtonian fluid, and Separan AP 30E, a polymeric solution with 2g/l H_2O, as non-Newtonian sample. Separan AP 30E is a polymer made by polymerizing acrylamide molecules, commonly used for water treatment, drilling fluids or enhanced oil recovery.

Apparatus: Rotational viscometer Rheotest II for the determination of the rheological measurements; and the laboratory facility, with recirculation loop or bypass, the thermostat T, gear pump P, pressure gauge M, overpressure valve V, control valve R, and the column S, presented schematically in Figure 7.

Experimental conditions: temperature: 25 (^oC), rotation speed between: 40 and 90 (RPM), pressure differences between delivery and suction: 0 - 4 (at). The pressure difference 1 (at) is equivalent with 98100 (Pa).

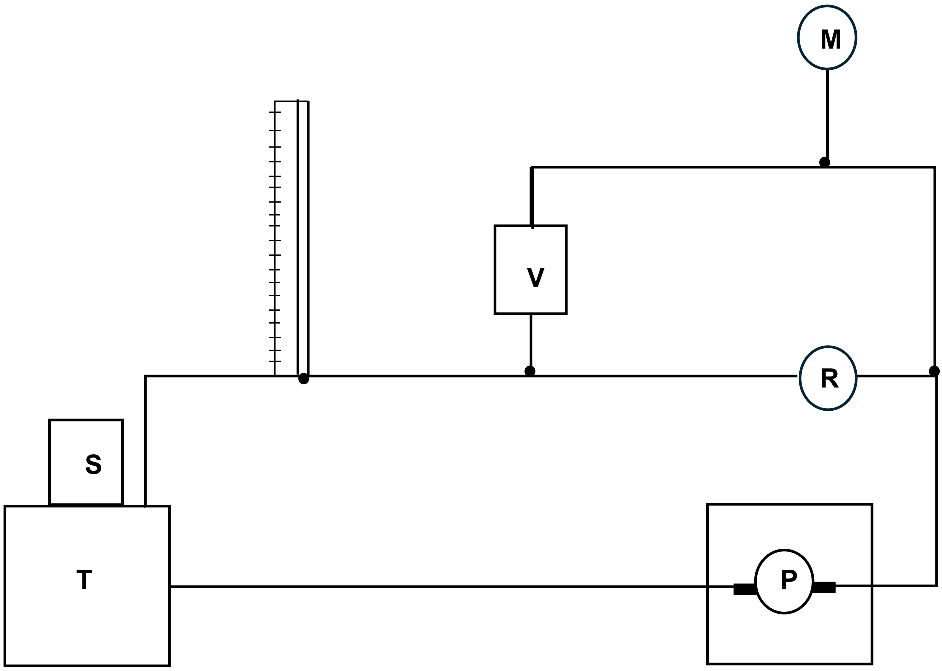

Figure 7. Experimental circuit for pressure difference measurement

The testing method offers the possibility of pumping the fluids at different pressures using magnetically coupled gear pumps with the speed adjusted in stages.

A constant pump rotation speed is set on the gear pump using the specific push button settings, starting with 40 RPM. The control valve R and the measured overpressure M on the bypass line, equipped with a pressure bypass valve V, allow us to determine, the discharge pressure.

The height of the liquid column S is measured, and the resulting volumetric flow rate G_v is determined from the corresponding calibration curve (see Table 1).

Minor deviations in the reproducibility of the measurements can be explained by physical structural modifications of the Separan due to mechanical stress (constant pumping in the circuit).

Table 1 shows the results obtained at different pressure between delivery and suction for each tested case.

Table 1. Measurement data for the operating behavior of the gear pump

Sample	Speed rotation of the pump [RPM]	Pressure diff. ΔP (at)	Height of the fluid h (mm)	Volumetric flow G_V (ml/min)
Glycerin/ Water	40	0	120	805
		1	100	750
		2	70	670
		3	45	600
		4	22	530
	60	0	265	1210
		1	240	1140
		2	213	1070
		3	185	985
		4	165	925
	80	0	405	1625
		1	384	1540
		2	352	1450
		3	325	1385
		4	302	1310
	90	0	535	1970
		1	525	1935
		2	495	1850
		3	470	1780
		4	440	1700
Separan AP 30E	40	0	100	690
		1	70	575
		2	10	330
		3	0	-
	60	0	200	1050
		1	180	1005
		2	120	770
		3	60	530
		4	0	-
	80	0	285	1420
		1	280	1400
		2	230	1200
		3	170	970
		4	105	705
	90	0	410	1890
		1	380	1800
		2	325	1580
		3	255	1300
		4	195	1070

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