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Research Article

EXPERIMENTAL STUDY OF THE FLOW OF VISCOUS NEWTONIAN FLUIDS IN A CENTRIFUGAL PUMP

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ABSTRACT

This paper analyzes the influence of viscosity and impeller rotation speed in the calculation of the flow and in the theoretical prediction of the performance of a centrifugal pump impeller. The evaluation of the viscous effects allows the prediction of the frictional losses of the impeller and a more correct evaluation of the operating characteristics than can be obtained with a perfect fluid. The viscosity modifies the values of the velocity distribution in the channels of the impeller and the deviation of the flow at the exit of the blade. The experiments were carried out with mineral oils of different viscosities varying between 96.10^{-3} Pa.s and 520.10^{-3} Pa.s and which are represented by a perfectly newtonian behavior.

Keywords: Experimental study; centrifugal pump; rheology; newtonian fluids; hydraulic performances.

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1. INTRODUCTION

The oil industry requires several types of installations and equipment. Among these are often found pumps of various types. Centrifugal pumps have a prominent place in the oil industry, characterized by their continuous operation; they are used in the field of shipping crude oil through pipelines from one unit to another. To accomplish this mission, pumping installations are necessary and indispensable, where the crude oil is collected from several wells, stored in storage tanks and then pumped to a region by means of centrifugal pumps, which are generally multi-stage. The availability of these pumps plays a very important role in the production; indeed, any failure can lead to a decrease in production.

Centrifugal pumps are widely used for many applications in the industry. However, the process of designing, manufacturing and experimental characterization of a centrifugal pump is a very tedious and expensive task for pump manufacturers with a large number of geometrical parameters to consider. The pumping of viscous fluids has applications that are not as important as those of water, but are very numerous. These include all petroleum products and lubricating oils for all industrial applications.

In order to minimize the costs associated with this process while improving the performance of a centrifugal pump, this study aims at developing a reliable and accurate experimental approach to study and analyze the complex liquid flows in a centrifugal pump in order to identify and predict the parameters improving its performance: head, efficiency and power.

Several works have shown that the properties of viscous newtonian and non-newtonian fluids have a remarkable influence on the hydraulic performance of centrifugal pumps compared to water [8]. For viscosities up to 1510^{-3} Pa.s the performance of centrifugal pumps does not vary and remains similar to that of water, but for viscosities between 15.10^{-3} Pa.s and 100.10^{-3} Pa.s there is a slight reduction in head, but a great decrease in efficiency due to the very high power consumption.J.L. Gulich [3] and Li Wen-Guang [6,7] experimented with centrifugal pumps of specific speed Ns less than 50 min-1 carrying viscous fluids. They showed that the drop in efficiency becomes very significant when the fluid viscosity exceeds 3.10^{-4} m^2/s.

J.L. Gulich [5] shows that the efficiency can decrease to a value of 50% when the viscosity is 12.10^{-4} m^2/s.

2. EXPERIMENTAL TECHNIQUES

2.1 Pumping system

The study was carried out on a pumping installation with the following components:

- A single-stage centrifugal pump with variable speed up to 3000 rpm and a maximum hydraulic power of 736 W

- A suction line with a diameter of 45 mm and a length of 600 mm, including a differential pressure gauge to measure the suction pressure and a valve to create the necessary pressure drop to make the pump cavitate

- A discharge line with a diameter equal to that of the suction line, about 450 mm long, with a differential pressure gauge to measure the pressure at the outlet

- A control valve to regulate the flow

- A motor adjusted on a spring scale to measure the torque

- A tachometer and a chronometer to measure the rotation speed

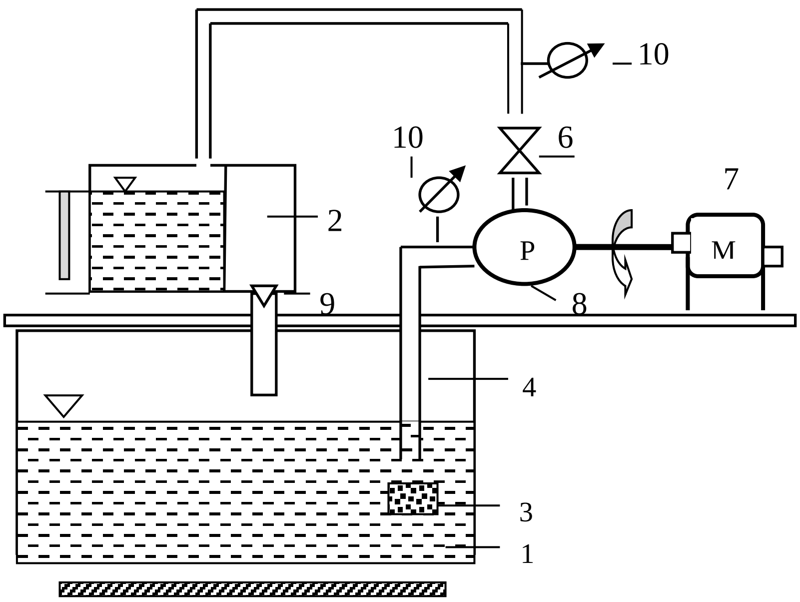

Fig.1. Diagram of the test bench

1. Upstream tank 2.Downstream tank 3. Strainer 4. Suction pipe 5.Discharge pipe
6. Discharge valve 7. Electric motor 8. Centrifugal pump 9.Drain valve 10.Pressure gauges

Table 1. Geometrical characteristics of the pump impeller

inlet diameter d_1 (mm)	outlet diameter d_2 (mm)	inlet width b_1 (mm)	outlet width b_2 (mm)	number of blades Z
108.7	**45,12**	**9,5**	**3,2**	**8**

2.2. Used rheometer

The apparatus used is a rotary viscometer with coaxial cylinders of the type "Rheomat 30" to which several measuring systems can be adapted (table 2). It is based on the measurement of a torque applied to a suspended solid element is due to the viscous forces induced by a second element in motion in the medium considered. In this viscometer the fluid element to be studied is placed in the annular cylindrical space between two concentric cylinders. The measuring body in the medium to be measured is driven by a DC electric motor at constant speed, the outer cylinder tends to rotate in the same direction under the influence of the viscosity force. The braking torque exerted by the substance on the body is then measured and displayed by the rotating system as reaction torque. But in all cases the torque exerted on the cylinder is directly related to the shear stress rx imposed on the fluid and the cylinder wall. Similarly, the known shear rate of the cylinder is related to the strain gradient $(\frac{du}{dr})$

Table 2. Viscometer measurement systems (A,B,C,D)

	R_1 (mm)	R_2 (mm)	(R_2-R_1) (mm)	(R_2/R_1) (mm)
A	45.7	48	2.3	1.05
B	30.1	37.8	7.7	1.26
C	13.7	19.9	6.2	1.45
D	7.5	14.9	7.4	1.99

Fig.2. Experimental rig of Viscometer

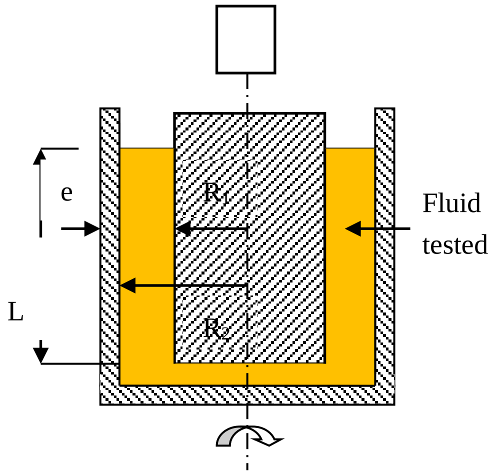

Fig.3. Couette viscometer

The equality of the moments of the forces gives us:

$$\tau(2\pi R_i L)R_I = 2\pi.R_I^2\tau.L = M \quad (1)$$

$$\tau = \frac{M}{2\pi R_i^2 L} \quad (2)$$

3. HYDRAULIC CHARACTERISTICS

The hydraulic characteristics of a centrifugal pump are studied experimentally by keeping the speed N constant and varying the flow rate Q, which changes the head H. This provides us with the relationship H = f(Q) called the head - flow curve or pump flow curve. By simultaneously determining the load of the drive motor whose efficiency is known, we calculate the power Pu on the shaft and the total efficiency of the pump as a function of the different flow rates Q. We thus obtain the experimental curves Pu = f(Q) and = f(Q) called respectively power curve and efficiency curve.

3.1 Head- flow curve

The head created by the pump is equal to:

$$H_P = \frac{p_2 - p_1}{\rho g} \quad (3)$$

3.2 Power curve

The various quantities defined below are usually used:

Power output of the pump Pu: power corresponding to the work done by the pump.

Q being the pumped flow and H the total head, we can write :

$$P_u = \rho g Q H_p \tag{4}$$

Power absorbed (consumed) by the pump, Pa: power supplied on the pump shaft

3.3 Efficiency curve

$$\eta = \frac{P_u}{P_a} \Rightarrow P_a = \frac{\rho g Q H_P}{\eta} \tag{5}$$

For any driven machine, a pump consumes more power than it supplies. The ratio of the power supplied and consumed is called the pump efficiency.

3.4. Specific speed

The specific speed Ns, of a pump is the speed of a geometrically similar pump, which would raise the unit of flow with a total load equal to the unit, so the expression of Ns will be :

$$N_S = N \frac{\sqrt{Q}}{(H)^{0.75}} \tag{6}$$

4. RESULTS AND DISCUSSIONS

4.1. Analysis of viscometric results

As the viscosity of the fluids depends strongly on the temperature, it is essential to have accurate viscosity measurements, whatever the system used a thermostatization to be able to maintain the temperature of the studied fluid constant during the whole experiment.

The viscometer used was without a temperature stabilization system. This temperature is due to the heat developed by the rotation of the inner cylinder of the viscometer and can influence the results. In our results we assumed that the temperature was constant or at least that it varies very little because of the short duration of the test.

The values of the studied viscosities are given in the following table:

Table 3. Values of the different oils studied

Oil	1	2	3	4	5	6
Viscosity (Pa.s)	96.10^{-3}	150.10^{-3}	230.10^{-3}	370.10^{-3}	415.10^{-3}	520.10^{-3}

Before proceeding to the experiments, we calibrated our viscometer with a standard fluid which is the glycerin.

The fluids that we studied are mineral oils whose viscosity varies from 96.10^{-3} to 520.10^{-3} Pa.s, the measurements were made at constant temperature (T = 20°) in a rotary viscometer with coaxial cylinders type "Rheomat 30". We present in Figure 4 the results of rheograms obtained. This result leads us to conclude that these mineral oils with paraffinic tendency present a Newtonian rheological model of constant viscosity of type:

$$\tau_{rx} = \mu \left(\frac{du}{dr}\right) \tag{7}$$

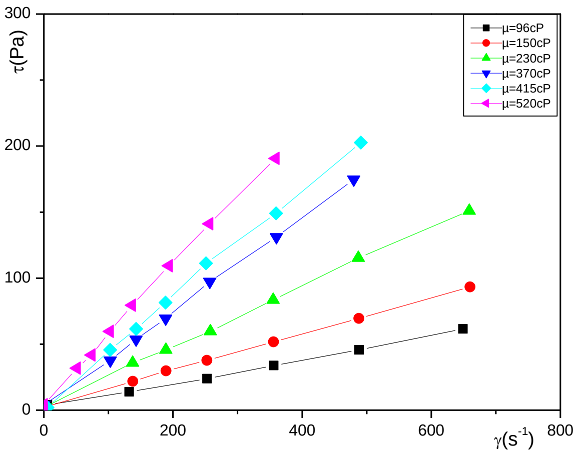

Fig.4. Rheogram of the oils used

4.2. Performance of the pumps

4.2.1 Calibration curve

The flow rate is measured by cubing, i.e. the volume that flows into the measuring tank during a given time.

Before starting the experiments, the measurement was calibrated using a volume method.

From the calibration curve (fig.5) we obtained a tank constant K=0.3021 liter per minute.

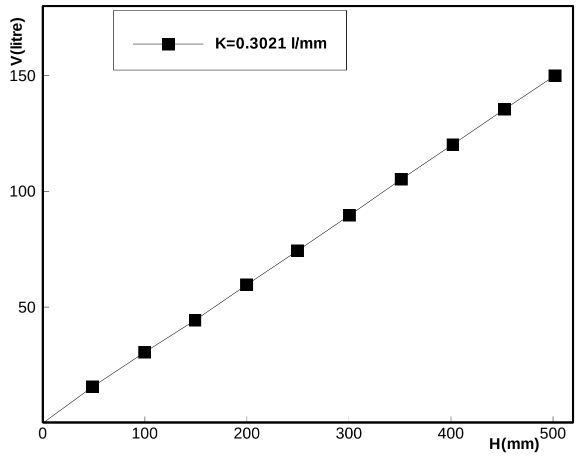

Fig.5. Calibration curve of the measuring tank

4.2.2 Influence of the rotation speed

Validation curves

The curves of figures 6 and 7 show a comparison between the results of the experiment of the present work and the theoretical results. This comparison shows a good agreement on the curves of the height and those of the power consumed for two speeds of rotation N=1400 rpm and 2200 rpm.

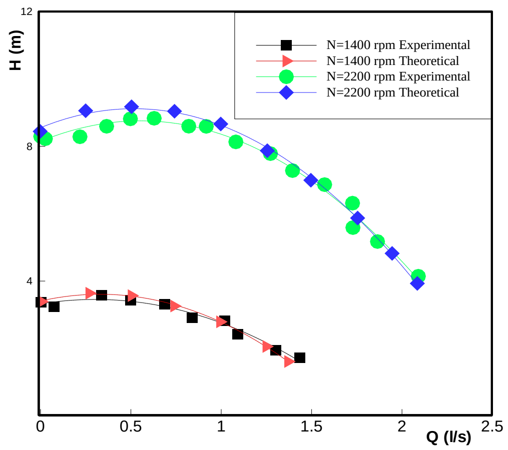

Fig.6. Head versus flow rate ($\mu=10^{-3}$ Pa.s)

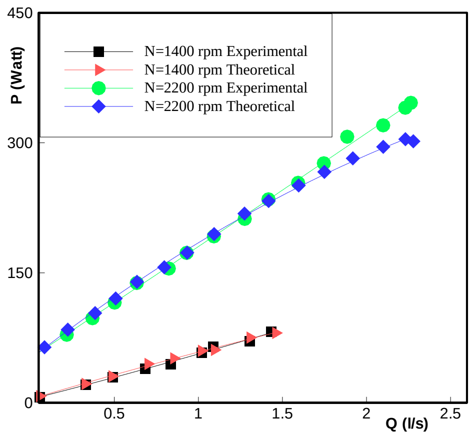

Fig.7. Power versus flow rate ($\mu=10^{-3}$ Pa.s)

To limit the capacities of the measuring devices of our installation, we proceeded to preliminary tests, these tests consist in determining the errors which we can make with the various measuring devices of the installation. The characteristic curves of the pump H= f(Q) and P = f(Q) were recorded for different pump rotation speeds varying from 1400 rpm to 2600 rpm with a step of 200 rpm.

The characteristic curves (fig. 8) and (fig. 9) found show that they vary in the same direction, i.e. that they increase with the increase of the rotation speed.

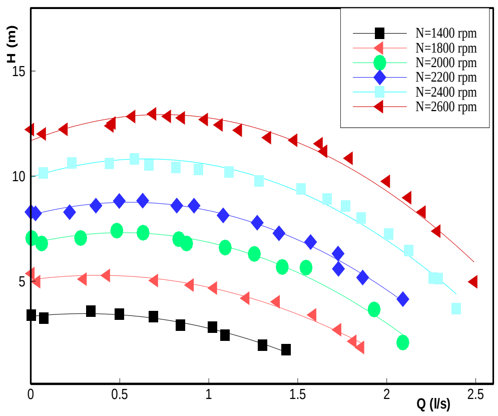

Fig.8. Head versus flow rate

(μ= 10^{-3} Pa.s)

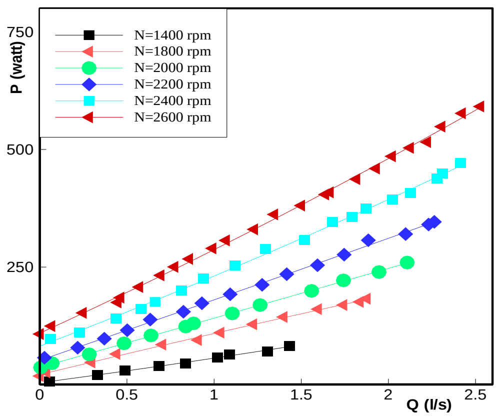

Fig.9. Power versus flow rate

(μ=10^{-3}Pa.s)

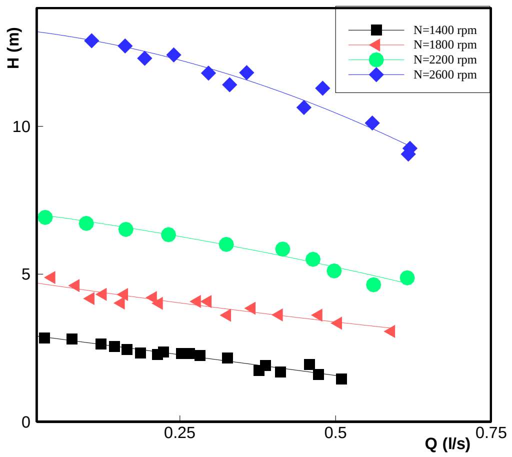

Fig.10. Head versus flow rate

(μ=230.10^{-3}Pa.s)

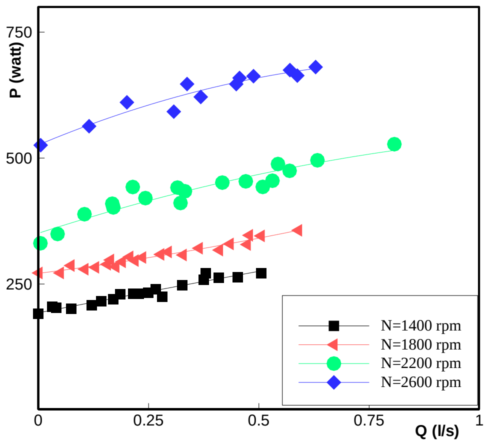

Fig.11. Power versus flow rate

(μ=230.10^{-3}Pa.s)

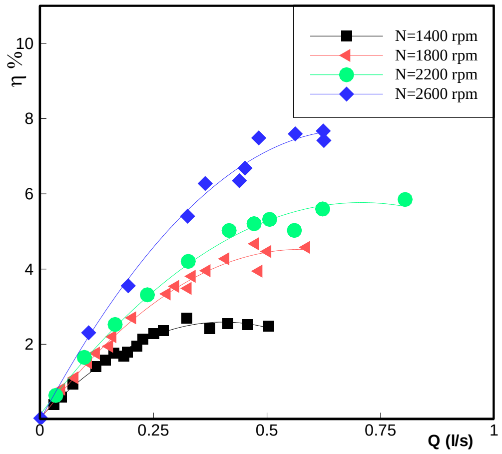

Fig.12. Efficiency versus of flow rate (μ= 230.10^{-3} Pa.s)

The measurement results are shown in figures 10, 11 and 12 where it can be seen that for a constant viscosity (230 .10^{-3} Pa.s) the network of curves H=f(Q), P= f(Q) and η=f(Q) at variable speed has the same appearance for all viscosities. All three characteristics vary in the same direction, i.e. they increase with increasing speed.

4.2.2 Influence of the viscosity of the studied fluids

Validation curve

A comparison of the H versus Qv curves and the efficiency versus flow rate for two dynamic viscosities of values 96.10^{-3} Pa.s and 370.10^{-3} Pa.s is shown on curves 13 and 14. This comparison shows a good agreement between the experimental and theoretical results.

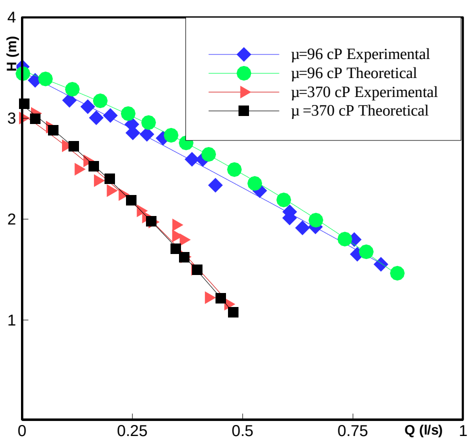

Fig.13. Head versus flow rate

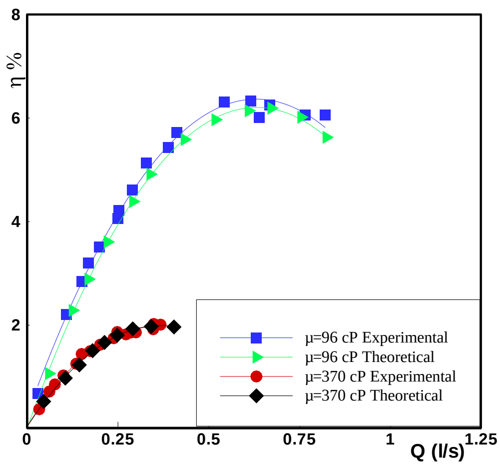

Fig.14. Efficiency versus rate

On figures 15, 16 and 17 we have represented the characteristics H = f(Q), Pu = f(Q) and = f(Q) at constant speed of rotation N = 1400 rpm for different values of viscosity except for two oils of higher viscosity, namely 415.10^{-3}Pa.s and 520.10^{-3} Pa.s, where the test was not carried out, on the one hand because the torque was greater than the capacity of the motor and on the other hand the capacity of the pump was too low to lift these very viscous fluids.

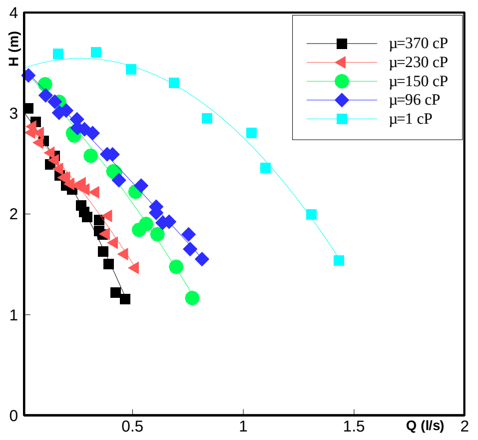

Fig.15. Head versus flow rate

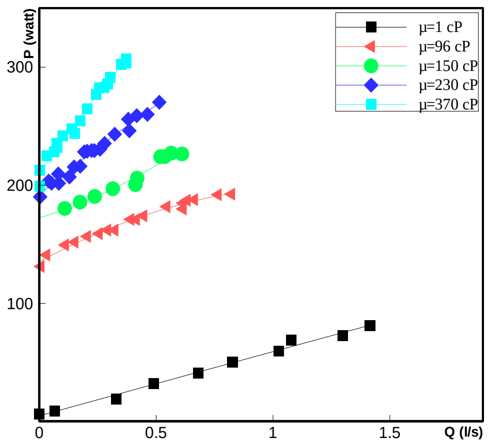

Fig.16. Power flow rate

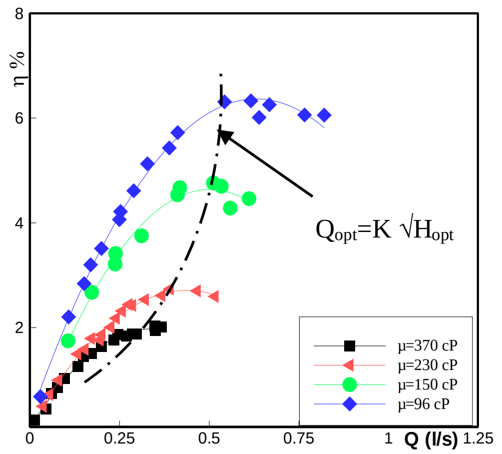

Fig.17. Efficiency versus flow rate

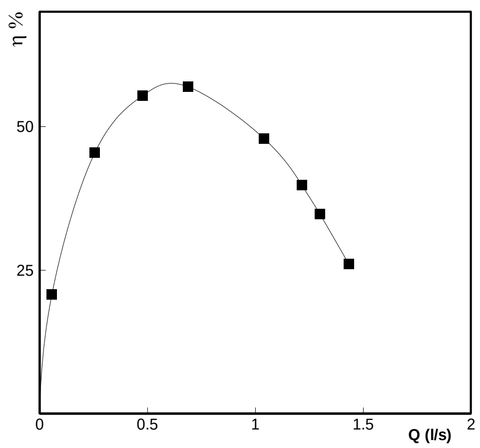

Fig.18. Efficiency versus flow rate ($\mu = 10^{-3}$ Pa.s)

For the curve H = f(Q) at constant flow rate we notice that there is a significant decrease of the head, we also notice on this curve that at closed valve (Q= 0) the head remains constant or varies very slightly independently of the viscosity. As the viscosity increases the curve becomes steeper, which reduces the operating range of the pump from 1.5 l/s for water to 0.5 l/s for oil with a viscosity of 370.10^{-3} Pa.s

For the power curves the trend is reversed, i.e. with increasing viscosity the power curves tend to increase, this is explained by the fact that it is necessary to increase the power to overcome the frictional losses created by the viscosity. The power consumption increases visibly with the viscosity. For example, for Q =0.5 l/s, the power supplied increases from 32 W for water to 340 W for oil with a viscosity of 370.10^{-3} Pa.s

On the other hand, the optimum value (max) for the efficiency curve decreases from 56% for water (Fig.18) to 2% for oil with a viscosity of 370.10^{-3} Pa.s; there is a significant reduction in pump efficiency for the transport of viscous fluids.

At constant speed, both the flow rate Q and the head H decrease as the viscosity increases. For example, the flow rate Q for oil with a viscosity of 370.10^{-3} Pa.s is almost three times lower than for water.

We can see from our results that the points of best performance are aligned on a parabolic curve of the form (fig.18): $Q_{opt} = K\sqrt{H_{opt}}$

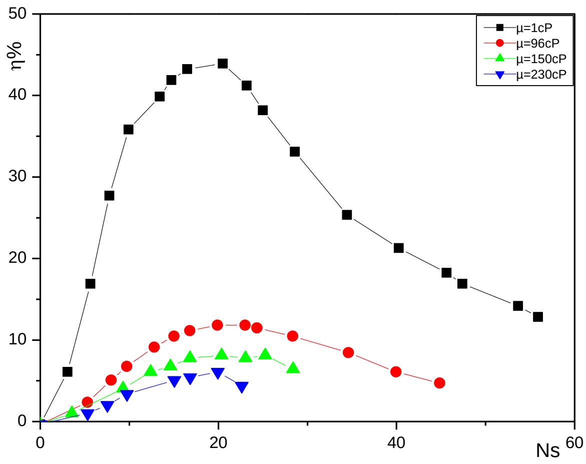

Fig. 19. Efficiency versus Ns

In Figure 19 we show the efficiency coefficient as a function of the specific number of revolutions, we can say that the specific speed has the same value at the points of best efficiency (optimal efficiency) and this independently of the viscosity. We also notice that beyond Ns > 50, the values of the efficiency coefficient become constant.

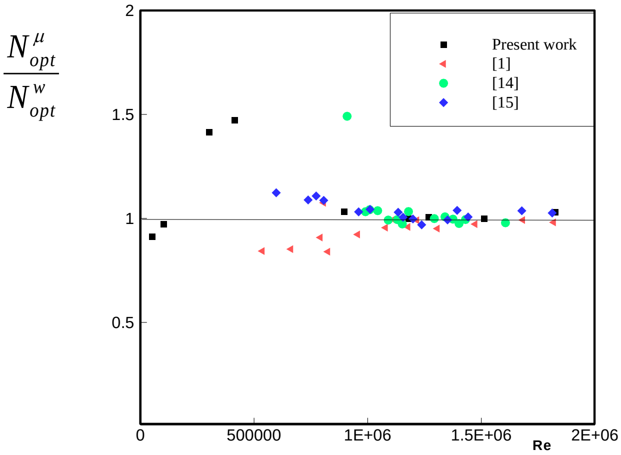

Fig.20. Ratio of the specific velocity as a function of Re at the points of best efficiency for viscous fluids and water

The ratio of specific speed for viscous fluids and water is close to unity for values of Re > 2.10^4. At lower Reynolds number, the values of this ratio vary between 0.8 and 1.5 according to the author and 0.8 to 1.0 according to other researchers (fig. 20)

5. CONCLUSION

Much research has been done on centrifugal pumps; the sizing, operation and limit of use of these centrifugal pumps to convey various newtonian and non-newtonian fluids. The performance of centrifugal pumps conveying complex fluids is the objective of this work.

When a centrifugal pump is used to transport a fluid much more viscous than water, the losses inside the pump increase and consequently the performances decrease (pressure and efficiency). When pumping water, the rotation of the impeller forces the liquid particles to follow the shape of the blades, giving them an optimal path from the eye of the impeller to the discharge; when the viscosity of the fluid increases, the particles cannot follow exactly the same path, resulting in more friction and loss of performance.

At constant speed, the head decreases as the fluid viscosity increases. At constant head, the flow rate Q for the 370.10^{-3}Pa.s viscosity sample is almost three times smaller than for water

The power consumption increases significantly with increasing viscosity, for a flow rate of

0.5 l/s the power output increases from 32 Watts (water) to 340 Watts for the 370.10^{-3} Pa.s viscosity sample. The efficiency coefficient for small centrifugal pumps is very low when the viscosity is high. Increasing the viscosity from 1cPo to 370.10^{-3} Pa.s caused a decrease in the efficiency coefficient from 56% to about 2%.

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