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STUDY AND EXPERIMENTAL ANALYSIS OF HYDRAULIC FLUIDS COMPRESSIBILITY WITH DIFFERENT VISCOSITIES

Felipe Resende de Souza

Luiz Felipe Pereira Scalabrini

Pontifícia Universidade Católica de Minas Gerais, Department of Mechanical Engineering, Belo Horizonte, Brazil
feliperesendebh@gmail.com; luiz.scalabrini@hotmail.com

Mara Nilza Estanislau Reis

Pontifícia Universidade Católica de Minas Gerais, Department of Mechanical Engineering, Belo Horizonte, Brazil
mara@pucminas.br; mara.nilza@terra.com.br

Abstract. Fluid compressibility is the capacity of the fluid to reduce its volume initially occupied as a function of the pressure applied to it. This capacity is influenced by the following properties: pressure, viscosity, temperature and specific mass. For certain industrial applications where the speed of actuation is not a major influence for higher production, the compressibility in the case of liquids can be disregarded. But for applications where large pressure variations and higher actuation speeds are required, this characteristic should not be neglected because the lower is the compressibility of the hydraulic fluid, the better is the response of the hydraulic system to the driven control. This is due to the fact that when compressing the hydraulic fluid there is a small contraction of its volume, this generates an empty space to be filled with more fluid before getting effective work in the hydraulic system. Thus, the compression of the liquid creates non-uniform movement, movement delay, pressure peaks and oscillations in the hydraulic applications. The properties of the fluids influencing the compressibility modulus, such as viscosity, have been defined in order to emphasize their importance in the hydraulic system. Thus, the objective of the present work is to experimentally study the fluid bulk modulus with different viscosities by evaluating the volume variation, when the pressure is increased in a hydraulic double acting cylinder (32/22 x 200 mm). The experimental methodology was implemented in a hydraulic bench of the company FESTO using two different hydraulic fluids: ISO VG46 and ISO VG68.

Keywords: Experimental, bulk modulus, hydraulic system.

1. INTRODUCTION

Bulk modulus is defined as a constant of proportionality between volume variation that a given volume of fluid undergoes and the pressure variation at which this volume is subject. In other words, the greater the bulk modulus, the less is the fluid compression at a given pressure applied on it. Thus, when compressing a hydraulic fluid there is a small contraction in its volume, reducing the efficiency of the system (Carneiro, 2013)

In order to minimize this problem, many scientists have published articles about this theme. George and Barber (2007) report the importance of studying the effects of compressibility on fluids operating at high pressures, proving experimentally how the bulk modulus affects the response time of a hydraulic assembly. Experiments evidenced by the authors have demonstrated the reduction of up to 67% of the efficiency of a hydraulic process through small variations in temperature and aeration of the fluid. Niezrecki, et al, 2004 proposed a new technique to determine the bulk modulus of a hydraulic fluid using a piezoelectric actuator coupled to a fluid system that contains compressed air and mechanical conformity. Kambic et al, 2014 studied the bulk modulus of ionic fluids and their effects on hydraulic systems, and found that the compressibility of those fluids is much lower than the standard mineral oils and even water. Therefore, they deduced that the reduction of volume found in ionic liquids make them practically incompressible when compared to the usual mineral oils, making them an excellent option for high-pressure hydraulic systems. Tsubouchi and Shinoda (2010) have developed a study on high viscosity fluids with high bulk modulus in order to improve the performance of hydraulic systems. Considering that some of the fluids frequently used had low viscosity to provide the reduction of the flow resistance, the authors observed how the bulk modulus was affected in detriment to that.

As manufacturers usually do not provide the oils' bulk modulus in their products and this is an important data for the improvement of efficiency in a hydraulic system. The present work studies the compressibility of two fluids (ISO VG46 and ISO VG68) with different viscosities by evaluating the volume variation due to the increase of the pressure applied

(between 30 and 160 bar) under condition of constant temperature during the tests in a double action cylinder (32/22 x 200 mm). Such temperature control was necessary to maintain the viscosity of the fluids in a constant range for the correct data acquisition.

2. BULK MODULUS CHARACTERISTICS

When studying pneumatic systems, which use compressed air, the fluid is treated as non-viscous. That is, no effort is required to move one plate relative to another regardless of this plate's velocity. However, the inclusion of the compressibility effect for the design of valves, cylinders and motors is fundamental (Negri, 2001).

Unlike pneumatic systems, in hydraulic systems, liquids such as mineral oils, water-based fluids and synthetic fluids (treated as viscous and, for the most part, as incompressible) are used. It is important to highlight that the static design of hydraulic systems is conducted considering an incompressible fluid, however, in the applications involving proportional or servo control, the variation effect of the specific mass with the pressure is crucial for the design and understanding of these systems (Pequeno, 2008).

As in practice, there are no ideal hydraulic fluids, all of them present a contraction in their volume when compressed. This generates an empty space that needs to be filled with more fluid, only by filling the entire path it is possible to get profitable work in a hydraulic installation. Therefore, all the working time spent by the pump filling such spaces is lost, being many effects caused in hydraulic and pneumatic systems due to such event, which are easily perceived by operators. These effects, among others, are caused by the bulk modulus that corresponds to the specific mass variation with the pressure and also with the temperature (Pequeno, 2008).

Hydraulic fluids compressibility is a determining factor for the understanding of hydraulic circuits behavior and their variation is directly linked to the thermal expansion of the working fluid. Hence, the bulk modulus directly interferes with the actuation of the hydraulic system. The change in volume due to the applied pressure generates a delay in the transfer of the hydraulic energy to the mechanical energy, there being no movement of a valve for instance. The need of a cylinder movement is requested by the operator, but there is response delay of the hydraulic system. Under conditions of rapid and high pressure variations, the fluid behaves like a hydraulic spring. In most cases, this implies limiting the response speed of a component or system to a given input signal, that is, the limiting of the dynamic behavior (Linsingen, 2001).

The bulk modulus is associated to its variation of the specific mass as a function of the pressure to which it is submitted. In the case of liquids, there is no analytical expression that models the behavior of the specific mass in a system, but it is known that it is influenced by pressure and temperature. In this situation, one can obtain an expression through the Taylor series expansion, neglecting second order and higher terms, resulting in Eq. (1) (Negri, 2001):

$$\rho = \rho_i \left[1 + \frac{1}{\beta} (P - P_i) - \alpha (T - T_i) \right] \quad (1)$$

Where:

ρ = fluid specific mass in $\frac{kg}{m^3}$;

ρ_i = fluid specific mass in a specific point in $\frac{kg}{m^3}$;

β = bulk modulus in Pa;

$(P - P_i)$ = pressure variation in bar;

α = isobaric thermal expansion coefficient;

$(T - T_i)$ = temperature variation in K.

This equation corresponds to the liquid's state, linearized at an operating point. The coefficients present in this equation can be obtained from tables in specialized books or from complete catalogs on hydraulic fluids, being defined as shown in Eq. (2) (NEGRI, 2001):

$$\beta = \rho_i \left. \frac{\delta P}{\delta P} \right|_{T_i} = -V_i \left. \frac{\delta P}{\delta V} \right|_{T_i} \quad (2)$$

Where:

$\left. \frac{\delta P}{\delta P} \right|_{T_i}$ = pressure change rate in a given temperature range in $\frac{bar}{\Delta K}$;

V_i = volume at a given point in m^3 ;

$\left. \frac{\delta P}{\delta V} \right|_{T_i}$ = pressure change rate in relation to the volume in a given temperature range in $\frac{Pa \cdot m^3}{\Delta K}$.

Defined as bulk modulus and expressed in Pascal [Pa] which establishes the rate of change of the specific mass as a function of the pressure variation in a given volume or otherwise, the pressure change rate that occurs due to the variation of the volume where the fluid is confined (Negri, 2001).

3. EXPERIMENTAL PROCEDURE

In order to obtain data about the difference of the bulk modulus of two different fluids (ISO VG46 and ISO VG68), the experimental methodology was implemented using a hydraulic bench from the company FESTO. That bench was composed by a hydraulic pump (3 cv), a closing valve, a 4/3-way directional valve, two analog gauges, a dial indicator, a double action cylinder and seven ¼ "flexible hose couplings. Figure (1) illustrates that, as follow:

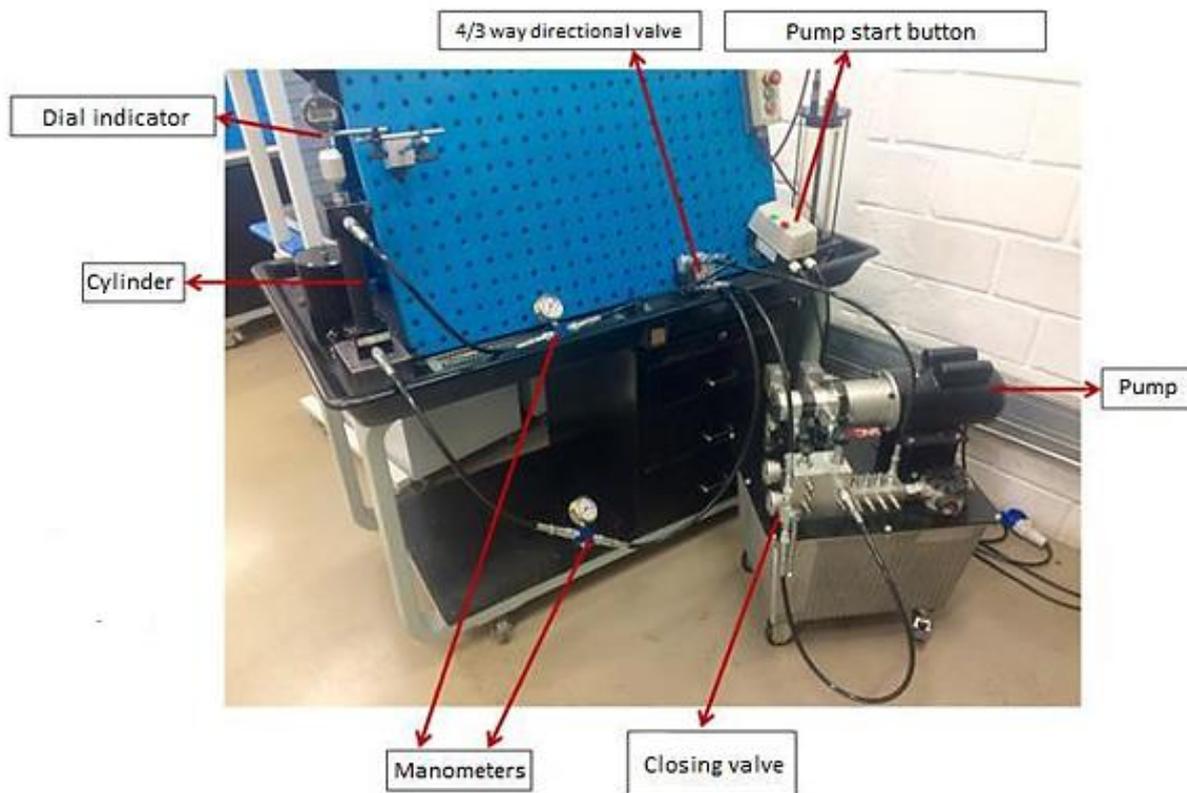


Figure 1 - Hydraulic bench from FESTO.

The displacement of the cylinder whose outlet was obstructed during the forward movement of the piston was measured by the use of a dial indicator, making it possible to evaluate the variation of the bulk module for different pressure values. The temperature of the fluid remained between 28 and 32 °C and calculations for the cylinder deformation were made so that the increased value of the total cylinder volume could be approached more accurately from the experimental reality.

A series of theoretical calculations that compose the elaboration of the bulk modulus for each fluid was applied. Thus, Fig. 2 represents the compression occurred in the cylinder (Carneiro, 2013):

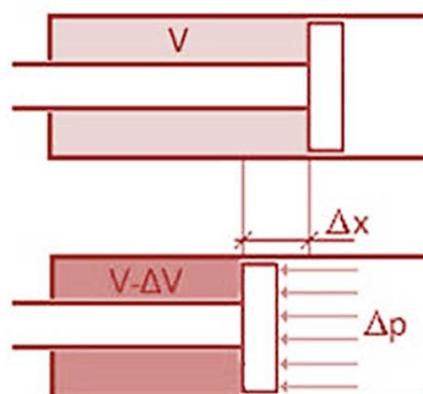


Figure 2 - Oil volume compression.

Considering that l e x_0 represent the the initial stroke and position of the cylinder, respectively, the volume contained in the secondary chamber of the hydraulic cylinder is described by Eq. (3) (Carneiro, 2013):

$$V = \pi(\phi_{piston}^2 - \phi_{rod}^2) \times (l - x_0)/4 \quad (3)$$

Where:

V = Volume contained in the secondary chamber in mm³;

ϕ_{piston} = Diameter of the piston in mm;

ϕ_{rod} = Diameter of rod in mm;

l = Cylinder stroke in mm;

x_0 = Cylinder starting position in mm.

And, knowing that the variation of the volume contained in the secondary chamber is given by Eq. (4) (Carneiro, 2013):

$$V = \pi(\phi_{piston}^2 - \phi_{rod}^2) \times \Delta x/4 \quad (4)$$

Where:

Δx = Variation of the chamber volume in mm.

It is assumed that the mean bulk modulus of the fluid will be given by Eq. (5) (Carneiro, 2013):

$$\beta = (l - x) \times \Delta p/\Delta x \quad (5)$$

Where:

Δp = Pressure variation in Pa.

In order to determine the compressibility curve of the studied fluid, pressure increases were made in the cylinder main chamber and the displacement values were recorded, as well as the pressure values in the secondary chamber (equal to the pressure in the main chamber of the cylinder multiplied by the ratio of areas 2:1). The pressure varied from 15 to 80 bar, and then in the secondary chamber was obtained 30 to 160 bar (Carneiro, 2013). Table 1 below shows the calculated volume increase values after the determination of the cylinder deformation.

Table 1 - Cylinder deformation (Increase in volume).

Secondary chamber pressure [bar]	Increasing in volume [mm ³]
30	121,87
40	179,04
60	255,09
80	327,82
100	393,23
120	477,50
140	548,10
160	620,82

To maintain the accuracy of the collected data, an uncertainty analysis was performed, where, for each calculated mean of the experimental results, an uncertainty value was assigned, referring to the combination of the uncertainties present in each measurement system. As a system of 7 measurements was used to collect each pressure applied to the cylinder, Eq. (6) was used to validate the results using the Chauvenet criterion (Mendes, 2012):

$$\frac{d_{max}}{\sigma} \leq 1,80 \quad (6)$$

Where:

d_{max} = Greater difference between the values obtained and the calculated mean;

σ = Standard deviation of the respective values obtained.

Based on these data, it was calculated the arithmetic mean, the standard deviation, the mean standard deviation and the combined uncertainty. For the expanded uncertainty, as the number of different measurements was less than 100, Student's t-distribution curve was used, with a coverage factor of 95% (Mendes, 2012).

4. RESULTS AND DISCUSSION

Initially, the cylinder volume increase was calculated according to the applied pressure. For the calculation, the Young's modulus for low alloy steels (200 GPa) was used, as shown in Eq. (7) (Reis, 2010):

$$\delta = (d \times \sigma)/E \quad (7)$$

Where:

δ = Deformation in mm;

d = Inner diameter mm;

σ = Tension in Pa;

E = Young's modulus in Pa.

The volume increase was added to the total volume value so that the volume would approach a real value. Based on this volume the compressibility modulus was calculated.

Table 2 and Table 3 show the measured and calculated values for the ISO VG68 oil:

Table 2 - Measured values for ISO VG68 (15 to 40 bar).

Pump pressure [bar]	15 bar	20 bar	30 bar	40 bar
Cylinder rod displacement [mm]	1,814	2,139	2,656	3,207
Displaced volume [mm]	657,500	750,622	883,890	1.044,445
Displaced volume [%]	0,775	0,885	1,042	1,231
Outlet gauge [kgf/cm ²]	27,571	39,000	61,143	80,000
Bulk modulus [Pa]	298.022.494	357.827.762	451.551.223	489.318.749
Sample standard deviation [mm]	0,0630	0,1090	0,0239	0,0659
Average sample standard deviation [mm]	0,0257	0,0445	0,0098	0,0269
Combined uncertainty [mm]	0,0326	0,0488	0,0223	0,0335
Expansion of uncertainty [mm]	0,0797	0,1194	0,0545	0,0820
Sample standard deviation [Pa]	7.172.276	10.120.824	15.871.026	20.764.177
Average sample standard deviation [Pa]	2.928.069	4.131.809	6.479.319	8.476.940
Combined uncertainty [Pa]	2.928.194	4.131.986	6.479.597	8.477.303
Expansion of uncertainty [Pa]	7.165.291	10.110.970	15.855.573	20.743.960

Table 3 – Measured values for ISO VG68 (50 to 80 bar).

Pump pressure [bar]	50 bar	60 bar	70 bar	80 bar
Cylinder rod displacement [mm]	3,866	4,496	5,024	5,497
Displaced volume [mm]	1.249,266	1.426,890	1561,664	1699,925
Displaced volume [%]	1,473	1,682	1,841	2,004
Outlet gauge [kgf/cm ²]	99,154	122,181	139,621	158,484
Bulk modulus [Pa]	503.070.776	533.068.449	545.123.525	565.465.789
Sample standard deviation [mm]	0,0786	0,0614	0,0979	0,0644
Average sample standard deviation [mm]	0,0321	0,0251	0,0400	0,0263
Combined uncertainty [mm]	0,0378	0,0321	0,0447	0,0330
Expansion of uncertainty [mm]	0,0925	0,0785	0,1094	0,0808
Sample standard deviation [Pa]	25.725.719	31.707.517	38.729.055	41.121.650
Average sample standard deviation [Pa]	20.503.705	12.944.540	15.811.070	16.787.843
Combined uncertainty [Pa]	20.504.156	12.945.094	15.811.663	16.788.563
Expansion of uncertainty [Pa]	25.703.669	31.676.646	38.691.140	41.081.613

For each measured pressure, the combined uncertainty was calculated, due to the necessity to verify the uncertainties of the measurements of both the comparator watch and the manometer.

Figure 3 shows the displacement of the cylinder rod (mm) versus the outlet pressure (Pa), measured through the comparator watch on the cylinder rod and the manometer positioned at the cylinder outlet, respectively.

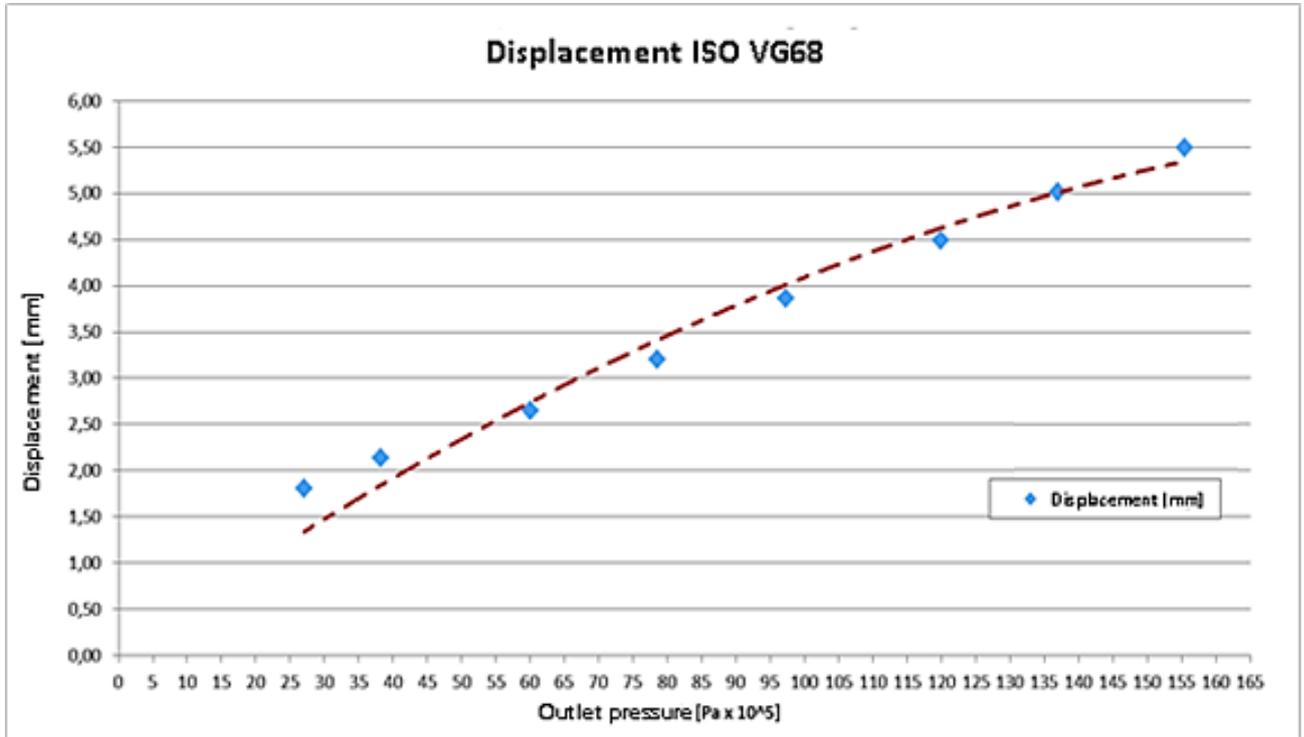


Figure 3 - Displacement of cylinder rod.

Figure 4 shows the calculated bulk modulus (Pa) versus the measured outlet pressure (Pa):

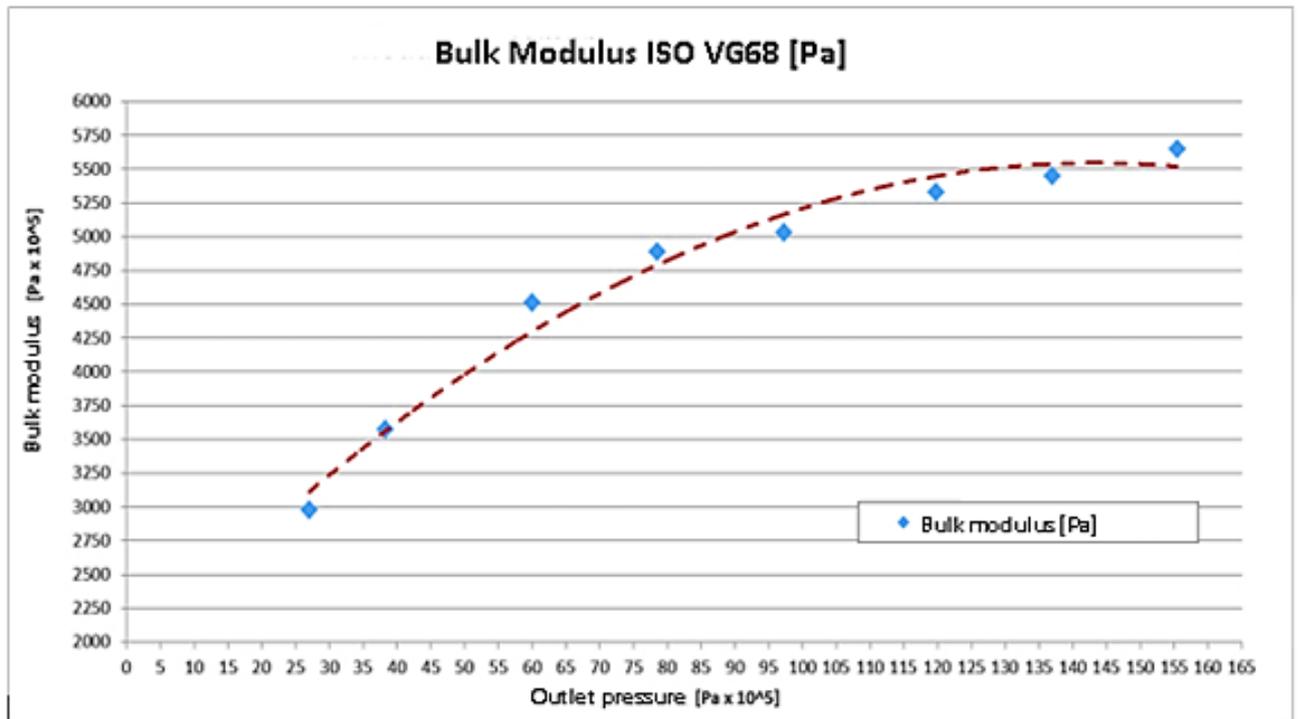


Figure 4 - Bulk modulus (ISO VG68).

Table 4 and Table 5 show the measured and calculated values for the ISO VG46 oil:

Table 4 - Measured values for ISO VG46 (15 to 40 bar).

Pump pressure [bar]	15 bar	20 bar	30 bar	40 bar
Cylinder rod displacement [mm]	1,991	2,403	2,966	3,571
Displaced volume [mm]	722,632	839,912	1.002,58	1.186,71
Displaced volume [%]	0,852	0,990	1,182	1,399
Outlet gauge [kgf/cm ²]	30,143	44,857	64,429	83,143
Bulk modulus [Pa]	297.262.399	366.937.533	427.382.317	458.470.256
Sample standard deviation [mm]	0,0943	0,0338	0,0312	0,0910
Average sample standard deviation [mm]	0,0385	0,0138	0,0127	0,0372
Combined uncertainty [mm]	0,0434	0,0243	0,0237	0,0422
Expansion of uncertainty [mm]	0,1061	0,0595	0,058	0,1033
Sample standard deviation [Pa]	7.823.839	11.644.752	16.717.678	21.577.304
Average sample standard deviation [Pa]	3.194.069	4.753.950	6.824.963	8.808.898
Combined uncertainty [Pa]	3.194.205	4.754.153	6.625.256	8.809.275
Expansion of uncertainty [Pa]	7.816.221	11.633.414	16.701.401	21.556.296

Table 5 - Measured values for ISO VG46 (50 to 80 bar).

Pump pressure [bar]	50 bar	60 bar	70 bar	80 bar
Cylinder rod displacement [mm]	4,000	4,621	5,167	5,816
Displaced volume [mm]	1.303,05	1.482,31	1.643,13	1.845,45
Displaced volume [%]	1,536	1,748	1,937	2,176
Outlet gauge [kgf/cm ²]	99,967	121,640	139,791	158,484
Bulk modulus [Pa]	492.435.009	519.148.184	534.056.183	538.390.589
Sample standard deviation [mm]	0,0400	0,0518	0,0845	0,0545
Average sample standard deviation [mm]	0,0163	0,0212	0,0345	0,0223
Combined uncertainty [mm]	0,0258	0,0291	0,0399	0,0299
Expansion of uncertainty [mm]	0,0632	0,0712	0,0976	0,0732
Sample standard deviation [Pa]	25.939.572	31.561.016	36.271.661	41.121.650
Average sample standard deviation [Pa]	10.589.786	12.884.731	14.807.844	16.787.843
Combined uncertainty [Pa]	10.590.240	12.885.283	14.808.478	16.788.563
Expansion of uncertainty [Pa]	25.914.317	31.530.288	36.236.346	41.081.613

The change from ISO VG68 oil to ISO VG46 oil with lower viscosity led to changes in the cylinder displacement. For the ISO VG46 oil, greater displacements were measured compared to ISO VG68 oil. It indicates a difference of 0.3 mm between the two hydraulic fluids.

Figure 5 shows the cylinder rod displacement [mm] versus the outlet pressure [Pa] for the ISO VG46 oil. The same measurement methods applied in ISO VG68 oil were used here.

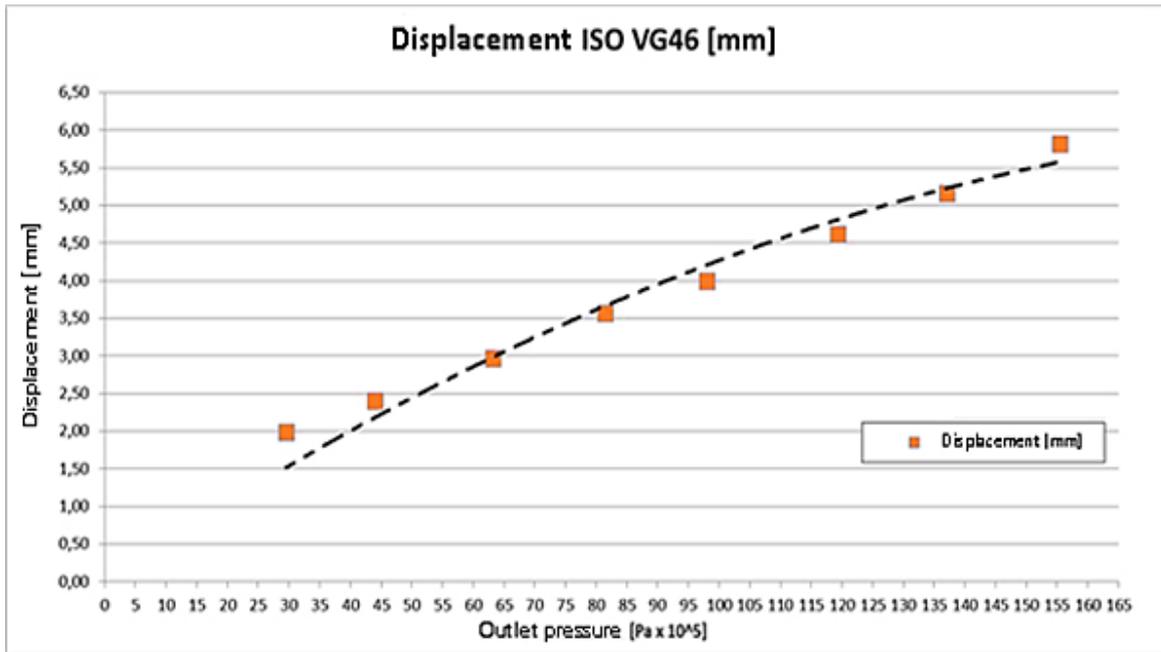


Figure 5 - Cylinder rod displacement (ISO VG46).

Figure 6 shows the calculated bulk modulus [Pa] versus the measured outlet pressure [Pa]:

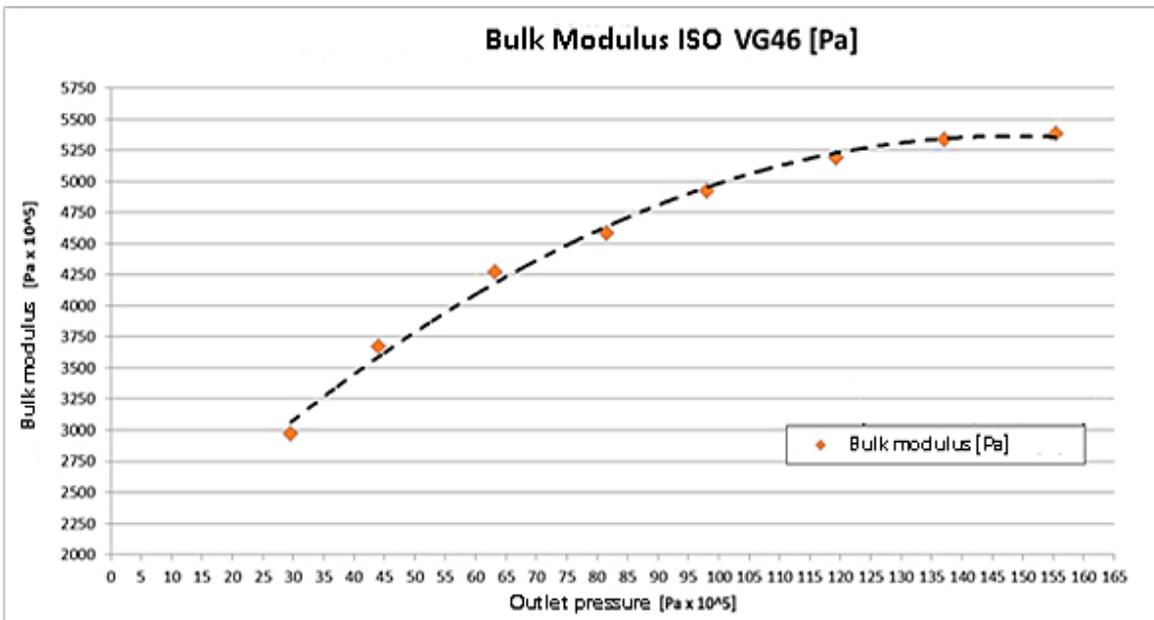


Figure 6 - Bulk modulus ISO VG46.

The bulk modulus changed from oil to oil. The bulk modulus for ISO VG46 was smaller than the ISO VG68 one. There was a difference of 270 bar at a 160 bar pressure in the outlet chamber.

Figure 7 shows the differences between the displacements for the two oils tested:

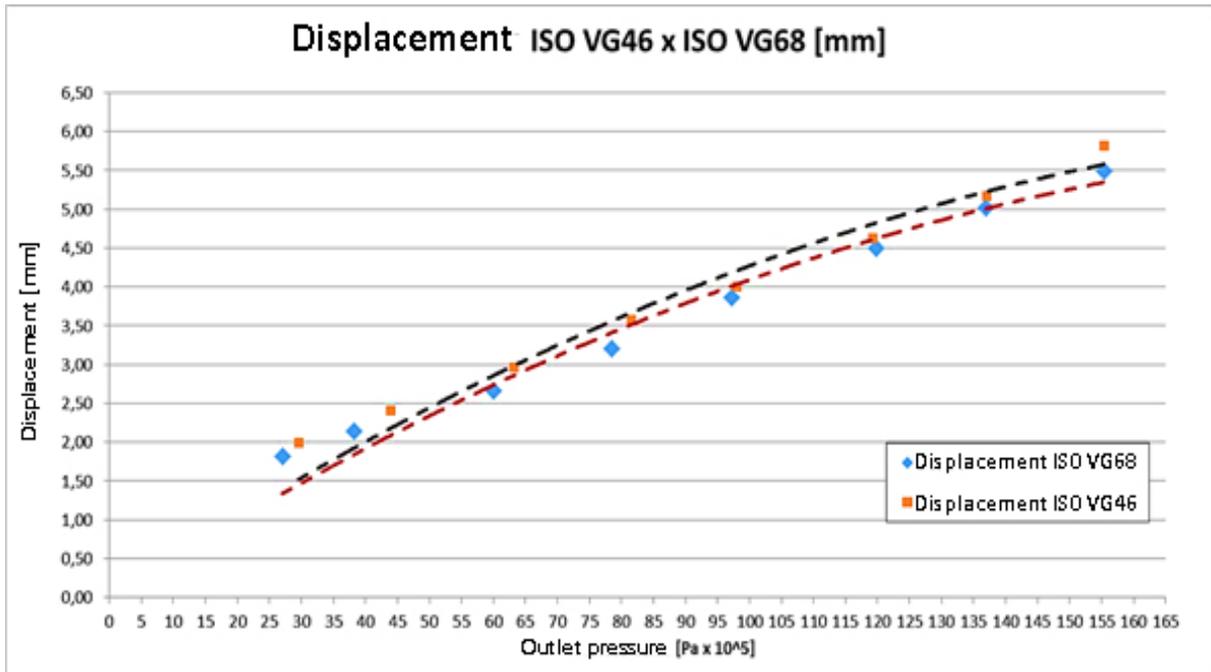


Figure 7 – Displacement ISO VG46 versus ISO VG68.

Figure 8 shows the differences between the bulk modulus for the two oils tested:

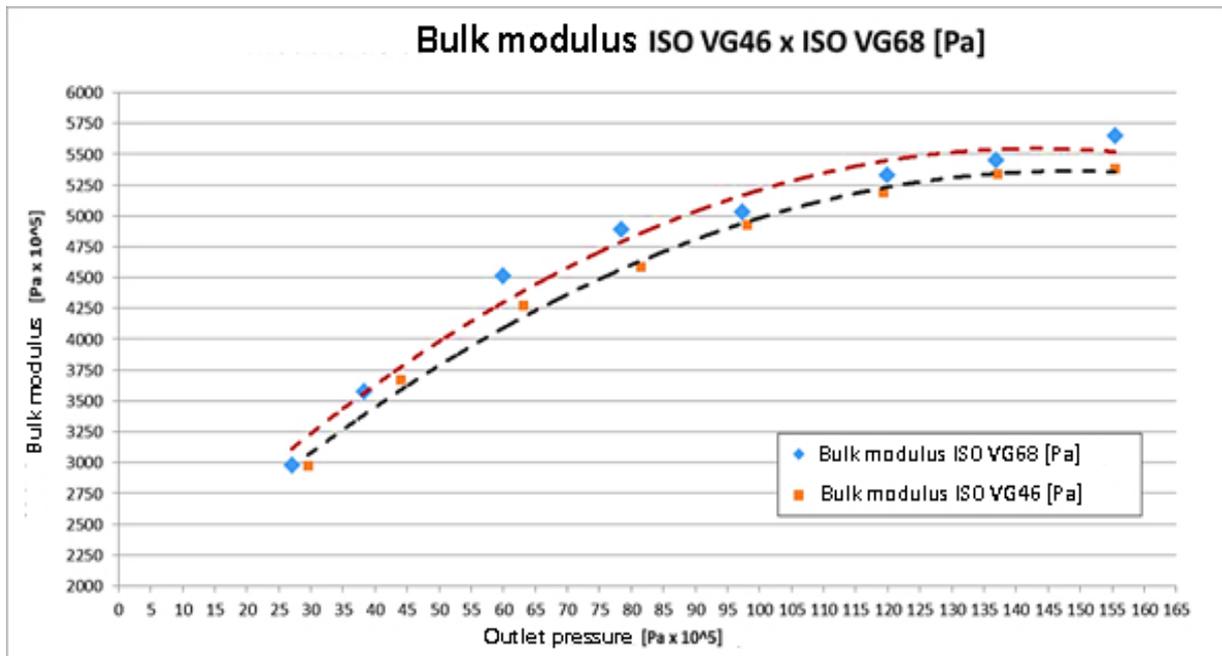


Figure 8 - Bulk modulus ISO VG46 x ISO VG68.

Therefore, the experimental acquisition in the hydraulic bench showed the differences between each oil used, with displacement difference around 0.2 mm. The highest displacement for both oils was verified at the higher pressure of the secondary chamber (160 bar).

The percentage of the displaced volume variation of 2% indicates how the compressibility of the oils should not be disregarded since for several applications in the industry the pressure values of the hydraulic systems exceed the 160 bar used in this experiment. The comparison between the compressibility modules showed the influence of viscosity on the displacement.

5. CONCLUSIONS

In making the measurements, the temperature of the fluid stayed between 28°C and 32°C, and the valve actuation mode was observed. After checking the measurements, the cylinder deformation calculations were made, so that the increased value of the total cylinder volume came closer to the experimental reality. Calculations for the bulk modulus were made based on the pressure on the outlet, approximately twice the input, and the volume change delta. Thus, the two oils used were compared, which showed that the displacement to ISO VG46 was higher than ISO VG68 due to viscosity.

In the case of the bulk modulus, the ISO VG46 oil had lower values when compared to ISO VG68 oil. The percentage value of the displaced volume was checked and the value of 2% was displayed for the maximum pressure of 160 bar in the secondary chamber.

Therefore, since in the experimental methodology, a lower pressure was applied than in relation to hydraulic systems used in some industries and a volume compression was verified in about 2%, the study of ways to use fluids with less compressibility is very important to avoid losses and improve the efficiency of hydraulic systems.

6. ACKNOWLEDGMENT

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