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A STUDY OF THE DEPENDENCE OF THE VOLUMETRIC EFFICIENCY OF A VANE PUMP ON PRESSURE AND VISCOSITY

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ABSTRACT

Hydraulic system design and component selection should take into account the performance capabilities of the hydraulic fluid. Selecting a hydraulic fluid with the proper viscosity is critical in order to obtain optimum system response and guarantee long-term performance. A fluid with too high a viscosity at low temperature will resist flow and may cause pump cavitation. The use of a fluid with insufficient viscosity at the highest operating temperature will result in poor volumetric efficiency and, in some cases, overheating and pump seizure. The use of the ASTM D 6080 classification and the NFPA recommended practice for viscosity selection criteria can provide improved guidance in selecting the proper hydraulic fluid.

Mobile equipment, with limited cooling capability, must frequently operate under high temperature conditions. If the oil viscosity is too low, excessive internal pump leakage will occur. Work completed in gear and vane pumps has shown that the Poiseuille law can be applied to predict the influence of pressure and viscosity on volumetric efficiency.

This paper demonstrates how an equipment user or designer can estimate the pump volumetric efficiency for a given hydraulic fluid, over a range of pressure and temperature conditions. This approach should simplify the selection of a hydraulic fluid with viscometric properties optimised to meet application performance demands.

Key Words: Pump, hydraulic fluid, viscometric properties

INTRODUCTION

Hydraulic systems are widely used in the manufacturing, construction, forestry, mining and transportation industries. Over the years, systems for the transmission and distribution of power have become increasingly sophisticated, their applications more numerous and their operating conditions, in terms of pressure and temperature, more demanding on the fluid. Selection of an appropriate hydraulic fluid has become a critical task for the operator. It is important to consider the operating conditions for pressure, minimum and maximum operating temperature, and recommendations provided by the pump manufacturer.

Viscosity is one of the most important criteria in the selection of a hydraulic fluid. At low temperature, excessive viscosity may result in poor mechanical efficiency, difficulty in starting and, wear. At high temperature, low viscosity will result in low volumetric efficiency, overheating, and wear. Pump and motor manufacturers often provide in their documentation hydraulic fluid recommendations covering:

- The maximum start-up viscosity under load
- The range of optimum operating viscosity
- The maximum and minimum operating viscosity

A system aimed at supporting equipment users in selecting hydraulic fluids with the appropriate viscosity was presented at the IFPE 2000 session [1]. It introduced the concept of the Temperature Operating Window for hydraulic fluids (TOW). The TOW corresponds to the difference between the temperatures at which an oil will reach respectively the lowest acceptable operating viscosity and the maximum start-up viscosity for a given pump. The National Fluid Power Association (NFPA) issued a recommended practice in which the acceptable operating viscosity for most pumps and motors was set from 13 to 860 mm²/s [2].

The TOW of conventional hydraulic fluids based on API Group I or Group II base stock can be easily calculated using the empirical MacCoull, Walther, Wright (MWW) relationship [3], where η is the dynamic viscosity in milliPascal seconds (mPa.s), °K is the temperature in degrees Kelvin, m is the correlation coefficient and b is a constant. The value of m and b are obtained using the kinematic viscosity at 40 and 100°C.

$$\mathrm{LogLog}(\eta) = -m*\mathrm{Log}(\,°K\,) + b \qquad \{\text{Equation 1}\}$$

If given hydraulic oil does not exceed a viscosity of 860 mm²/s at the lowest operating temperature of the equipment, this fluid will provide adequate performance at low temperature start-up. If the viscosity of the given fluid remains higher than 13 mm²/s at the highest operating temperature, this fluid will provide adequate performance at peak thermal loading conditions.

Some oil applications do not fall within the TOW system because of wide operating temperature ranges or the pump manufacturer recommends a viscosity range of less than the 13 to 860 mm²/s range used by the TOW system. In these applications, the optimum fluid viscosity may be determined by using a variation on the ASTM D 341 viscosity temperature chart known as the ALTOW system.

While this system provides some help to the equipment user in selecting the proper fluid for a given range of operating temperatures, it does not provide information on the actual pump performance over that range of conditions. Our objective was to determine the relationship between the volumetric efficiency of a pump and the operating pressure, temperature and actual hydraulic fluid viscosity.

Earlier work completed using a small gear pump [4] had shown that the Poiseuille law could be used to estimate the volumetric efficiency as a function of pressure and fluid viscosity. In order to increase the usefulness of this approach, we wanted to verify its applicability to other types of pumps. Our first step was to analyse pumping data from a Vickers V-104 vane pump. The original data was presented in SAE paper 750693 by Stambaugh and Kopko [5]. In a second step, a test program was conducted in a Vickers V20 vane pump using conventional and high VI oils. In the following, only data on the conventional oils will be presented. A future publication will deal with the performance of high VI oils both in terms of volumetric efficiency and fluid operating temperature.

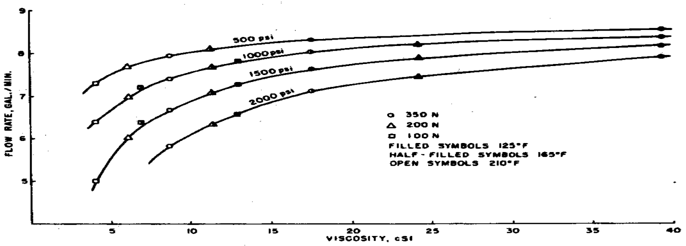


Fig. 1 — **Effect of fluid viscosity and operating pressure on pump performance**

MODEL DEVELOPMENT

ANALYSIS OF VICKERS V-104 VANE PUMP DATA

In their SAE 750693 paper, the authors used a Vickers V-104 vane pump driven by a 20 horsepower electric motor at 1200 rpm. This equipment was originally incorporated into a test loop used for testing hydraulic fluids according to ASTM D 2882.

In order to determine the relationship between pump discharge flow rate, operating temperature, and fluid viscosity, three Newtonian oils, which were 100N, 200N and 350N were tested at various temperatures and pressures. We used in our analysis the pressure, temperature and flow units reported in the referenced paper. Pressure was varied from 500 to 2000 psi in 500 psi increments (3,448 to 13,793 kPa in 3,448 kPa increments). Temperature effects were studied at 120 °F, 165 °F, and 210 °F (49°C, 74°C, and 99°C). The results shown in Figure 1, which was scanned from the original document, indicate that discharge flow rate is a smooth function of viscosity at each of the test pressures.

This work provided a useful relationship between pressure, temperature and viscosity but only for the four pressures used in this program. In order to increase the utility of these data, we would need to be able to use them for predicting the actual flow rate at any pressure falling within the range 500 psi to 2000 psi (3,448 to 13,793 kPa). For this purpose, we tested the applicability of the Poiseuille law that we found to adequately describe the actual flow rate of a gear pump as a function of pressure and viscosity [4].

According to the Poiseuille law, the actual flow rate (Q_a) is equal to the nominal flow rate of the pump (Q_n) less the leakage taking place in the pump (Q_l). Q_l is itself proportional to the difference between the pump discharge pressure (P_d) and the pump inlet pressure (P_i) divided by the dynamic viscosity of the oil (η).
$Q_a = Q_n – C*(P_d – P_i)/\eta$ {Equation 2}

C is a geometrical factor that is characteristic of the pump. If we neglect the inlet pressure (P_i), which is small relative to the discharge pressure (P_d), we obtain: $Q_a = Q_n – C*P_d/\eta$ {Equation 3}

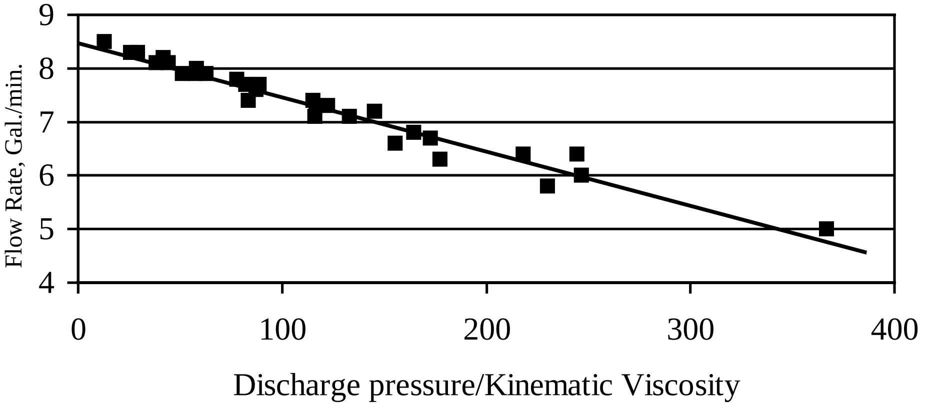
We digitalized the data from Figure 1 to obtain estimates of Q_a. We used the viscometric data given on the three Newtonian oils to calculate their viscosity at the three test temperatures using the MWW equation {1}. Since no information was made available on the density of the oils, we used the kinematic viscosity (KV) in our work. Numerical data are shown in *Table 1*.

Table 1: Flow rates (gallons/minute) as a function of kinematic viscosity and discharge pressure from SAE 750693.

	Flow rate at a given Pressure			
Viscosity, mm^2/s	500 psi (3,448 kPa)	1000 psi (6,896 kPa)	1500 psi (10,345 kPa)	2000 psi (13,793 kPa)
4.09	7.3	6.4	5.0	
6.08	7.7	6.8	6.0	
6.88		7.2	6.4	
8.69	7.9	7.4	6.7	5.8
11.28	8.1	7.7	7.1	6.3
12.87		7.8	7.3	6.6
17.21	8.3	8.0	7.6	7.1
23.92		8.2	7.9	7.4
39.12	8.5	8.3	8.1	7.9

Using these data, we have plotted in Figure 2 the actual flow rate as a function of the ratio discharge pressure over kinematic viscosity. We observe that there is a linear relation between flow rate and the ratio of pressure over kinematic viscosity which confirms that, in a first approximation, the Poiseuille law provides a good estimate of the actual flow rate over the range of pressure and viscosity used by the authors.

Figure 2: Flow rate versus the ratio P_d/kinematic viscosity from SAE 750693



We obtained by linear regression analysis the following least square equation:
$Q_a = 8.50 - 0.0102 * P_d/(KV)$ {Equation 4}

The coefficient of determination, R^2, is equal to 0.96.In Equation 4, the nominal flow rate of the pump at 1200 rpm is 8.50 gallon/min. The geometrical factor C is equal to 0.0102. The pressure is measured in pounds per square inch (psi).In addition to providing an estimation of the actual flow rate as a function of pressure and viscosity, Equation 4 can be modified to provide an estimate of the volumetric efficiency (V_E) of the pump under a variety of conditions.

Volumetric Efficiency = 100 * Actual flow rate/Nominal flow rate or:
$V_E = 100 * Q_a/Q_n$ {Equation 5}
Since $Q_a/Q_n = 1 - C * P_d/(Q_n * KV)$ we obtain:
$V_E = 100 * (1 - C * P_d/(Q_n * KV))$ {Equation 6}
Using the value of C and Q_n from the regression analysis we obtain the following equation for P=2000 psi (13,793 kPa).
$V_E = 100 * (1 - 2.4/KV)$ {Equation 7}

Therefore, we can easily estimate the volumetric efficiency of the Vickers V-104 pump knowing the viscosity of the fluid. In particular, we can calculate that the volumetric efficiency is equal to approximately 73% for a viscosity of 9 mm²/s, which corresponds to the minimum operating viscosity recommended by this OEM for mobile vane pumps.We can also easily determine at which kinematic viscosity a given volumetric efficiency will be reached at 2000 psi (13,793 kPa):
KV in mm²/s = $240/(100 - V_E)$ {Equation 8}

For example, a volumetric efficiency of 60% will be obtained, at 2000 psi (13,793 kPa), with a fluid having a kinematic viscosity of 6.0 mm²/s. Volumetric efficiencies of 90% and higher will be achieved with fluids having a viscosity greater than 24 mm²/s.

TEST PROGRAM WITH THE VICKERS V-20 VANE PUMP ON NEWTONIAN OILS

The Poiseuille law offers an easy way to select the proper fluid under a given operating pressure on the basis of the minimum volumetric efficiency that is required for economical operations. Additional work is required to further prove its applicability over a wider range of conditions and for both Newtonian and non-Newtonian oils. For this purpose, we have used a Vickers V-20 pump driven by a 20 horsepower motor at 1200 rpm. Thermocouples were located about 150 mm before the pump inlet, immediately after the pressure regulator and, in the reservoir. The schematic of the test stand is shown in Appendix 1.

TEST PROCEDURE

After flushing the test loop and installing a new filter, 20 liters of test oil were charged into the reservoir. The pressure was then set to the desired level using the throttle valve. When the oil temperature reached the targeted level, duplicate flow rates measurements were made. They consisted in measuring the time needed for 113.55 liters (30 gallons) of oil to go through a totalizing flow meter. The oil temperature was taken at the inlet and outlet of the pump. Inlet temperature increased during the flow rate measurement and the average was used to compute an estimate of the oil viscosity entering the pump using the MWW equation {1}.

TEST MATRIX

We evaluated three Newtonian oils, an ISO 22, 32 and 46. Their viscosities are given in *table 2.*

Table 2: Viscometric inspection of the Newtonian oils

Physical Properties	ISO VG 22	ISO VG 32	ISO VG 46
Kinematic Viscosity at 40 °C, mm²/s	22.30	31.33	46.01
Kinematic Viscosity at 100 °C, mm²/s	4.33	5.21	6.79
Viscosity Index (VI)	101	94	101

Flow rate measurements were done at four pressures:
No applied back pressure, $< 0.34 \times 10^6$ Pa (50 psi)
6.89×10^6 Pa (1000 psi)
10.34×10^6 Pa (1500 psi)
13.79×10^6 Pa (2000 psi).
Targeted test temperatures were 50, 65 and 80 °C.

ANALYSIS OF THE FLOW RATE DATA AT NO APPLIED BACKPRESSURE

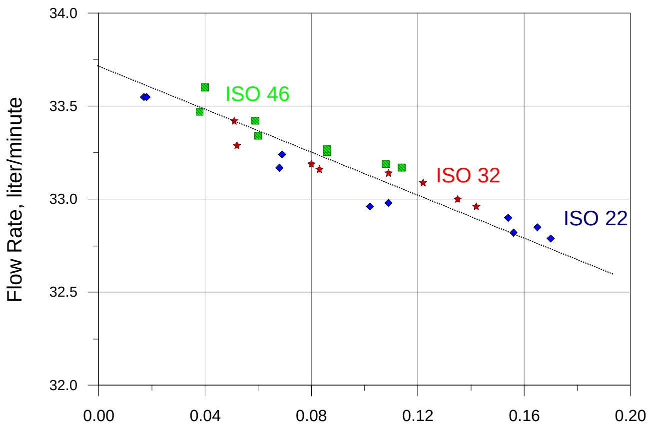
The average flow rate data obtained on each of the oils at the three test temperatures are shown in *table 3.*

Table 3: Average flow rate at no applied backpressure.

Test Oil	ISO VG 22	ISO VG 32	ISO VG 46
Flow Rate, L/min.	33.40	33.38	33.33

The average flow rate appears essentially independent from the oil viscosity. However, by plotting the flow rate as a function of the reciprocal of the average kinematics viscosity, we obtain a very different picture of the dependence of flow rate on viscosity. This relationship is shown in Figure 3. Even at the very low backpressure created by the piping between the pump outlet and the oil reservoir, the flow rate decreases slightly as viscosity decreases. This further confirms that the Poiseuille law is applicable to our system even under very low discharge pressure.

Figure 3: Dependence of the pump flow rate at no backpressure on oil viscosity.



By linear regression analysis, we obtained the following least square equation with a coefficient of determination, R^2, of 0.89.

Flow rate = 33.64 –4.94/KV {Equation 9}

ANALYSIS OF THE FLOW RATE DATA FOR NEWTONIAN OILS UNDER PRESSURE

We have computed for the three Newtonian oils the ratio P_d/KV for the three test pressures and the three test temperatures. As indicated before, all flow rates were measured in duplicate and the complete test program on each oil was run in triplicate. We ended up with a total of 54 flow-rate measurements per oil. To enable the comparison with the results from the SAE 750693 paper, pressure is expressed in psi units.

We completed a regression analysis on the data collected on each oil and then on the complete set of results. *table 4* summarizes our findings.

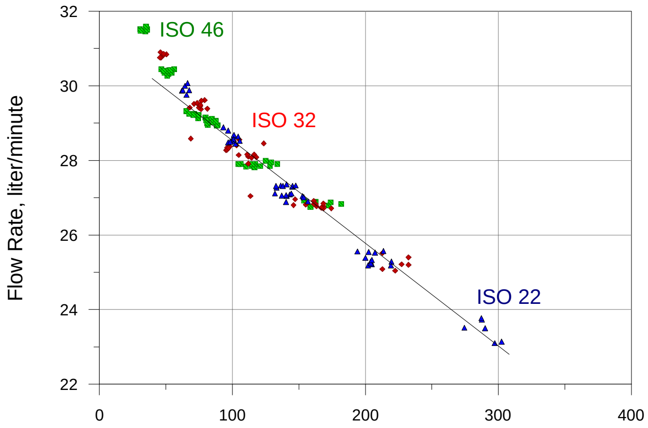
Table 4: Regression analysis for the Newtonian oil data in

Grade	Intercept	Slope	R^2
ISO VG 22	31.39	-0.0285	0.978
ISO VG 32	31.63	-0.0296	0.941
ISO VG 46	32.70	-0.0334	0.929
All oils	31.70	-0.0302	0.962

Every test oil follows the Poiseuille law. Some minor differences were observed between the oils in terms of intercept and slope. The higher the ISO grade the higher the intercept and the lower the slope. These differences may result from the fact that we used the average viscosity computed at the average inlet temperature. The average temperature increases during the time needed to complete the viscosity measurement as a result of the energy transferred to the fluid. The rate at which viscosity changes with temperature is not linear, as is evident from the MWW equation {1}.

We have plotted in *Figure 4* the flow rates obtained on the three test oils.

Figure 4: Dependence of the flow rate of Newtonian oils on pressure and viscosity.



Combining all test results provide us with the following equation with flow rates in liter/minute, pressures in psi and viscosity in mm^2/s:

$Qa = 31.70 – 0.0302*P_d/KV$ {Equation 10}

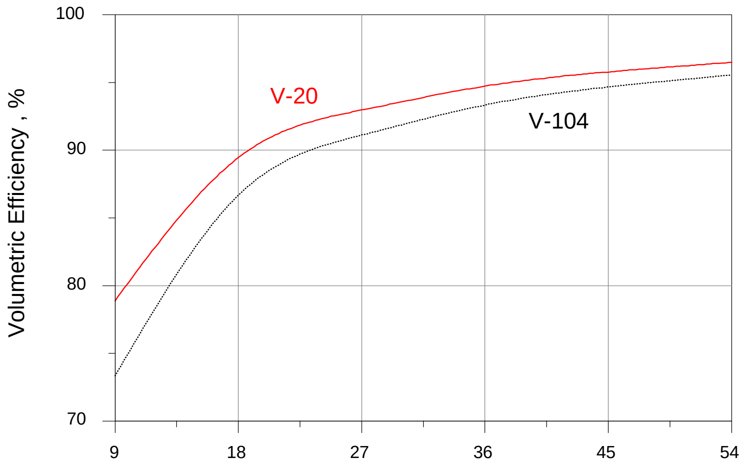
Comparison with the equation 4 obtained for the Vickers V-104 pump using the SAE 750693 data shows that the flow rate in the Vickers V-20 is slightly less dependent on viscosity.

Table 5: Flow rate and volumetric efficiency for Vickers vane pumps.

Pump	Flow rate, liter/minute	Vol. Efficiency at 2000 psi, %
Vickers V-104	$Qa = 32.20 – 0.0384*P_d/KV$	100*(1-2.4/KV)
Vickers V-20	$Qa = 31.70 – 0.0302*P_d/KV$	100*(1-1.9/KV)

The volumetric efficiency of the two pumps has been computed between 9 and 54 mm^2/s which is the range of operating viscosity specified by the manufacturer for mobile vane pumps. This data is shown in Figure 5.

Figure 5: Volumetric efficiency as a function of viscosity for the V-20 and V-104 pumps.



VOLUMETRIC EFFICIENCY AS A FUNCTION OF TEMPERATURE

The relationship between viscosity and volumetric efficiency at a given pressure can be used to determine at which viscosity a given level of volumetric efficiency will be attained. Using the MWW equation {1} we can then determine at which temperature an oil will reach this volumetric efficiency.

Hydraulic oils are often described using their ISO grade and their VI. The ISO grade corresponds to a nominal viscosity at 40°C. It is possible to calculate the viscosity at 100°C of an oil knowing its viscosity at 40°C and its VI [5]. Using the viscosity at 40°C and 100°C, the MWW equation {1} enables us to calculate at which temperature a given viscosity and thus, a certain level of volumetric efficiency, will be reached.

We have shown in *Table 6* how this approach could be used for the most common ISO grades for two different viscosity indices. Considering that a viscosity of 9.5 mm²/s will result in 80% volumetric efficiency, we obtained the corresponding temperatures. It can be seen that a 50-unit VI increase corresponds to an increased temperature at which 80% volumetric efficiency is obtained (5.0 °C for ISO 32, 7.6 °C for ISO 46 and, 10.7°C for ISO 68).

This example shows how one can select a hydraulic fluid based on the need to meet a given level of volumetric efficiency.

Table 6: Temperatures at which a given volumetric efficiency is reached as a function of the ISO grade and VI.

KV 40 °C, mm²/s	VI	KV 100 °C, mm²/s	Temperature for 80% efficiency, °C
32	100	5.36	74.5
32	150	6.26	79.5
46	100	6.72	84.7
46	150	8.13	92.3
68	100	8.69	96.1
68	150	10.88	106.8

It is also possible to determine the range of temperature (TOW) associated to a range of viscosity. In turn, this range of viscosity can be associated, as shown above, to a range of volumetric efficiency. We have calculated in *Table 7*, the TOW corresponding to the range of operating viscosity recommended by Vickers for mobile vane pumps. Three common ISO grades and two different viscosity indices have been included. We had calculated earlier that in the case of the Vickers V-20, the viscosities of 54 and 9 mm²/s correspond to 96.5% and 78.9% volumetric efficiency respectively.

From *Table 7* we can determine that a 50 unit VI increase corresponds to a TOW increase of 6.8°C for the ISO 32 fluid, 8.5°C for the ISO 46 fluid and 10.3°C for the ISO 68 fluid, based on volumetric efficiency.

Table 7: TOW in Vickers V-20 for the range of operating viscosity 9 to 54 mm²/s.

KV 40 °C, mm²/s	VI	Temp. for 78.9% V_E (°C)	Temp. for 96.5% V_E (°C)	TOW for 96.5% to 78.9% V_E (°C)
32	100	76.5	29.5	47.0
32	150	81.9	28.1	53.8
46	100	86.9	36.8	50.1
46	150	94.9	36.3	58.6
68	100	98.4	44.6	53.8
68	150	109.6	45.5	64.1

CONCLUSIONS

- Earlier work showed that the Poiseuille law could be used for predicting the actual flow rate of a gear pump as a function of viscosity and pressure.
- Using data obtained in a Vickers V-104 vane pump on three Newtonian oils over a range of pressure from 500 to 2000 psi (3,448 to 13,793 kPa), we showed that the Poiseuille law could adequately predict the actual flow rate of this vane pump as a function of viscosity and pressure.
- The Poiseuille law can also be used to determine the volumetric efficiency of a vane pump as a function of viscosity and pressure.
- A test program using a Vickers V-20 vane pump was completed at four pressures and three different temperatures with three Newtonian oils. Analysis of the flow rates showed that the Poiseuille law could be used over the range of 50 to 2000 psi (3,448 to 13,793 kPa) for predicting the actual flow rate of this pump as a function of viscosity and pressure.
- Comparisons of the equations obtained for the Vickers V-104 and V-20 vane pumps showed that internal leakage in the V-20 is less dependent on viscosity.
- We used the models discussed above to demonstrate the benefits achievable by increasing the viscosity index in terms of volumetric efficiency and enlargement of the range of temperature corresponding to a given range of volumetric efficiency.

- Our models can benefit OEMs and hydraulic fluid users in recommending or selecting the proper fluid for their equipment based on the maximum operating pressure and oil temperature in service.

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APPENDIX 1

Vickers V-20 Pump Loop Diagram