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Effect of Operation Time on Oil Viscosity and Pump Efficiency

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ABSTRACT

The objective of this work is to determine the relevance of the after-shear viscosity of multigrade hydraulic fluids to volumetric efficiency. For that purpose, we have analyzed flow rate data as a function of time obtained in several hydraulic pumps using a variety of fluids. This group includes the Eaton-Vickers V20 and V104 vane pumps, and a Denison T6C mobile vane pump. We have contrasted the decrease of kinematic viscosity of the test oils to the stability of the flow rate. This analysis has enabled us to assess the relative role of the in-service viscosity, as seen by the pumps, and of the kinematic viscosity of the sheared oils on volumetric efficiency of the pumps.

If a shear test that adequately represents the severity of the service is used, the fluid's after-shear kinematic viscosity can be used to estimate the volumetric efficiency of a pump. Alternatively, one can use the dynamic viscosity under high shear rate for that purpose.

The analysis suggests that even though the kinematic viscosity decreases over time, the in-service viscosity seen by the pump only changes slightly with time. Consequently, if an oil provides adequate volumetric efficiency during the first hours of operation, it will continue doing the same even after extended operation.

INTRODUCTION

The viscosity of hydraulic fluids is often classified according to ASTM D 2422, "Viscosity System for Industrial Fluid Lubricants". This system suffers from severe limitations since the lubricant is characterized only by its kinematic viscosity at 40 °C. This information alone is not of much use to a lubricant user or an equipment manufacturer since the equipment does not operate exclusively at this temperature. Furthermore, with the development of oils containing VI Improvers, the viscosity at 40 °C cannot serve as a basis for extrapolating viscosity at lower and higher temperatures.

The limitations of ASTM D 2422 have led several industry groups to look for better ways of characterizing the oil viscosity at both low and high temperature. The efforts of ASTM resulted in a new performance classification designated as ASTM D 6080. The classification included the definition of a low temperature grade, the "L" grade, and provided information on the viscosity and VI of the oil after shear in the Sonic test (ASTM D 5621). In Europe, CETOP also tried to develop a classification system that included a low temperature grading and information on the viscosity of the oil after shear in the KRL test (CEC L45-A-99). Finally, NFPA issued a recommended practice, T2.13.13-2002, to help equipment users select the proper fluid based on a) the viscometric requirements of specific hydraulic pumps and b) the minimum and maximum operating temperatures to which the fluid will be subjected.

The interest in defining a user friendly and efficient system lies in the fact that viscosity plays a major role in equipment efficiency. In the case of a fluid containing VI Improver, the viscosity and VI of the fresh oil may not be indicative of its performance under high temperature and high shear rate conditions. If the fluid viscosity decreases too much as a result of the permanent or temporary shearing of the VI Improver, this may result in low pump flow rate and excessive increase in fluid temperature. To address this concern, we analyzed several pumping studies to a) assess the rate at which viscosity and flow rate changed with time under high pressure conditions and b) identify the shear test that will best correlate with the viscosity loss that occurred in the equipment.

After reviewing data that have been published using medium pressure (140 bars) vane pumps, we will consider data obtained in a high pressure vane pump (250 bars). Our objective will be to determine the rate at which the pump flow decreases with test time and, using models for the pump leakage, to assess under which conditions the oil viscosity should be determined in order to provide a good estimation of the pump flow rate.

REVIEW OF MEDIUM PRESSURE VANE PUMP DATA

In this section we will review data that have been generated using Eaton-Vickers vane pumps operating at a maximum pressure of 139 bars. These data have been reported in the SAE papers SAE 750693[1] and SAE 901633[2] .

EATON VICKERS V104 PUMP DATA

R.L. Stambaugh and R.J. Kopko published data [1] that were generated in an Eaton-Vickers V104 vane pump. The pump was driven by a 20 HP electric motor at 1200 rpm. This equipment was originally incorporated in a loop used for testing oils according to ASTM D 2882.

Measurement of pump flow rate with Newtonian oils. In order to determine the relationship between pump flow rate and viscosity, three Newtonian oils 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 (34.5 to 138 bar in 34.5 bar 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. The higher the pressure, the higher the rate at which flow rate decreases when decreasing viscosity. This observation led us to consider the applicability of the Poiseuille law that we found to adequately describe the actual leak rate of a gear pump as a function of pressure and viscosity [3].

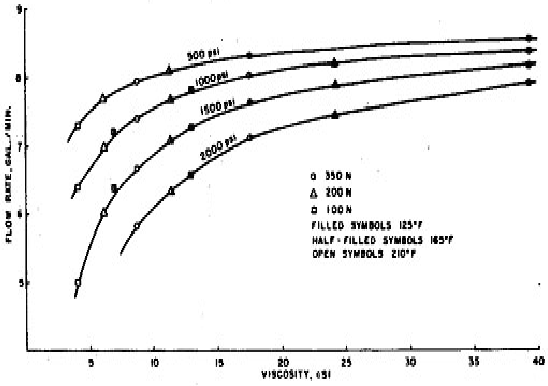


Figure 1: Effect of Fluid Viscosity and Operating Pressure on Pump Flow Rate

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, if it follows the Poiseuille law, 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).

$$Q_a = Q_n - C*(P_d - P_i)/\eta \qquad (1)$$

C is a geometrical factor that is characteristic of the pump. If we neglect the inlet pressure

(Pi), which is small relative to the discharge pressure (Pd), we obtain:

$$Q_a = Q_n - C^*P_d/\eta \qquad (2)$$

We digitalized the data from Figure 1 to obtain estimates of Q_a. We used the viscometric data given in the reference paper on the three Newtonian oils to calculate their viscosity at the three test temperatures using the MacCoull, Walther, Wright (MWW) relationship [4]. Since no information was made available on the density of the oils, we used the kinematic viscosity in our analysis. 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

	Flowrate (gal./min.)			
	Pressure			
Viscosity (mm²/s)	500 psi (34.5 bar)	1000 psi (69.0 bar)	1500 psi (103.5 bar)	2000 psi (138 bar)
4.09	7.3	6.4	5	
6.08	7.7	6.8	6	
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	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 plotted in Figure 2 the actual flow rate as a function of the ratio discharge pressure over kinematic viscosity. We observed a linear relation between flow rate and the ratio of pressure over kinematic viscosity which confirmed that, in a first approximation, the Poiseuille law provides a good estimate of the actual leakage rate over the range of pressure and viscosity used by the authors.

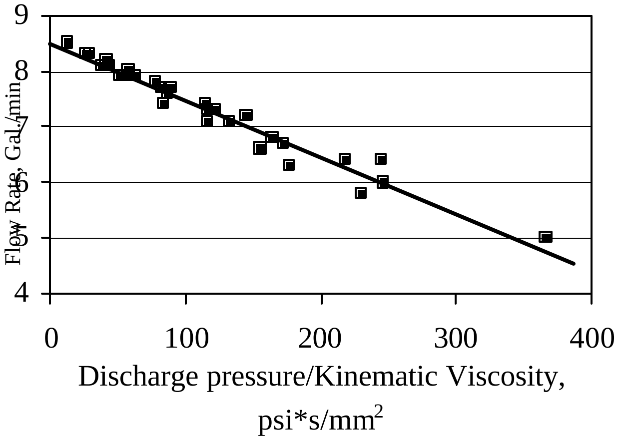


Figure 2: Flow Rate versus the Ratio P_d/Kinematic Viscosity from SAE 750693

We obtained by linear regression analysis the following least square equation:

$$Q_a = 8.50 - 0.0102^*P_d/(KV) \qquad (3)$$

The coefficient of determination, R², is equal to 0.96.

In Equation 3, 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).

Evaluation of high VI oils

The authors evaluated 11 high VI oils based on four different VI Improver chemistries. These oils were evaluated at 2000 psi (138 bar) for 100 hours. The flow rate was measured periodically and samples were taken to determine the viscosity of the oil corresponding to the flow measurements.

The permanent viscosity loss as a function of time obtained on the six fluids that were based on polymethacrylate (PAMA) VI Improvers is shown in Figure 3. The loss of viscosity expressed in terms of Shear Stability Index (SSI) ranges from 3 to 76%. A definition of the SSI is given in Appendix 1.

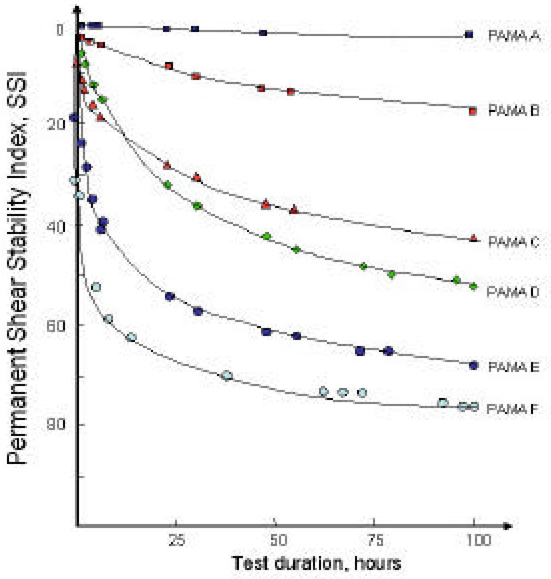


Figure 3: Permanent Shear Stability of PAMA VI Improvers in V104C Vane Pump Test

On the other hand, the flow rates obtained with these six oils changed only slightly with time. The largest decrease in flow rate obtained with the least permanently shear stable oil is only 5%. Most of this decrease takes place at the beginning of the test. This result is shown in Figure 4.

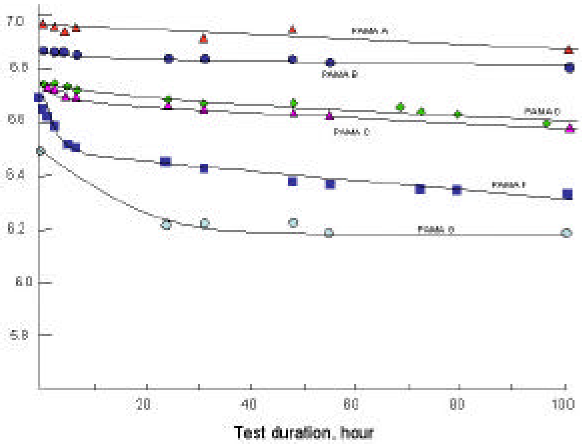


Figure 4: Effect of VI Improvers on Pump Flow Rate in V104C Pump Test

Since flow rate is dependant, for a given pressure, on the oil viscosity seen by the pump (in-service viscosity), the authors concluded that the in-service viscosity of the oils changed only slightly with time. The in-service viscosity is equal to the fresh oil viscosity less the combined effect of permanent and temporary viscosity losses, the sum of which should thus only show minor increase with test time.

The authors concluded that high shear viscosity measurements done on the sheared oil could be used to provide a good estimate of the pump flow rate. Alternatively, the kinematic viscosity of the used oil or the high shear viscosity of the fresh oil could also serve as a basis for a reasonable estimate of pump performance.

EATON-VICKERS V20 DATA

In the late 80's and early 90's efforts were devoted to the development of an improved way to classify the viscosity of hydraulic fluids. The outcome of this work was the ASTM D 6080 Standard Practice for Defining the Viscosity Characteristics of Hydraulic Fluids. Data reported by R.L. Stambaugh, R.J. Kopko and T.F. Roland in 1990 [2] contributed to the definition of this ASTM standard. The authors evaluated a series of polymer-containing fluids in a modified ASTM D 2882 pump loop to determine both permanent viscosity loss and flow rate change as a function of test time.

In this work, six reference oils coded HSO-01 to HSO-06 were evaluated. Included were three hydraulic fluids and three other high VI fluids often used in hydraulic equipment (one automatic transmission fluid and two SAE 10W-30 engine oils). These fluids represented four different VI Improver chemistries so that the results could be generalized to all types of fluids used in hydraulic equipment.

A summary of their physical properties is shown in Table 2

Table 2: Physical properties of HSO fluids

Oil Code	Fluid Type	KV @40 °C mm²/s	KV @100 °C, mm²/s	VI
HSO-01	Hydraulic	47.98	8.73	161
HSO-02	Hydraulic	38.29	7.83	181
HSO-03	Hydraulic	31.78	6.24	151
HSO-04	ATF	36.39	7.70	192
HSO-05	Engine Oil	72.08	10.90	141
HSO-06	Engine Oil	69.45	11.28	155

These six fluids were evaluated in an ASTM D 2882 pump loop in which the Eaton-Vickers V20 pump was substituted for the normal V104C. Test conditions were as defined in the ASTM method except that the test was interrupted every 25 hours in order to measure flow at 34.5, 69, 103.5 and 138 bar. All tests were run at a temperature of 65.6 °C. A new temperature control was used to improve the precision of flow rate measurements. This permitted control of the temperature within 0.5 °C compared to 3 °C in prior studies.

<ins>Permanent viscosity loss as a function of test time</ins>

The viscosity of the six test oils at 100 °C and 40 °C was determined at 10 hour intervals. The viscosity at 100 °C for the last run of each fluid was plotted versus test time in Figure 5.

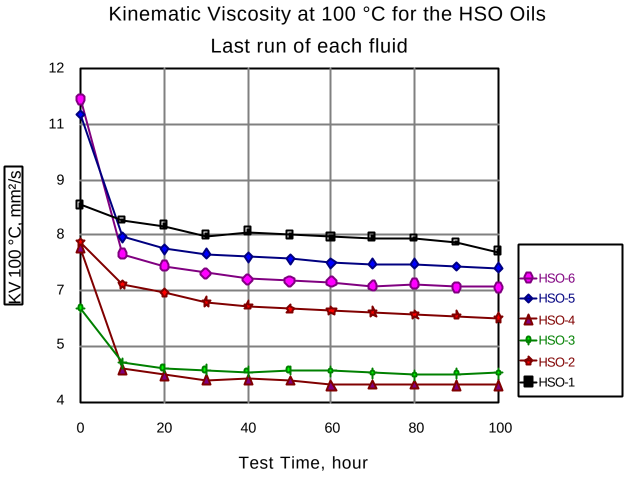


Figure 5: Viscosity at 100 °C of the HSO Oils as a Function of Time in Pump Test

We observed for some oils a dramatic permanent viscosity loss, especially for the ATF and the two engine oils. However, for all oils, viscosity approached equilibrium after 10 to 20 hours of service in the pump loop. Although none of the fluids reached true equilibrium, the rate of change became very low, in the order of less than 0.4 mm²/s per 100 hour.

We have compiled in Table 3, the viscosity and percentage of viscosity loss of the fluids at the end of the tests that used the improved temperature control.

Table 3: Viscosity of Test Oils at the End of the V20 Pump Test

	Sheared oil viscosity in mm²/s		Viscosity loss in %	
Oil code	40 °C	100 °C	40 °C	100 °C
HSO-01	43.46	7.66	9.4	12.2
HSO-02	31.87	6.01	16.8	23.2
HSO-03	24.23	4.58	23.8	26.6
HSO-04	20.91	4.39	42.5	43.0
HSO-05	46.61	7.22	35.3	33.8
HSO-06	41.11	6.76	40.8	40.1

Flow rate measurements

During the course of the test, flow rates were measured at 25 hour intervals. Flow rates were taken by measuring the time for 113.6 liters (30 gallons) of fluid to pass through a totalizing meter. The only data reported were those obtained at 103.4 bars (1500 psi) and 137.9 bars (2000 psi). At pressures below 103.4 bars, there was insufficient viscous heating to maintain the fluid temperature at 65.6 °C.

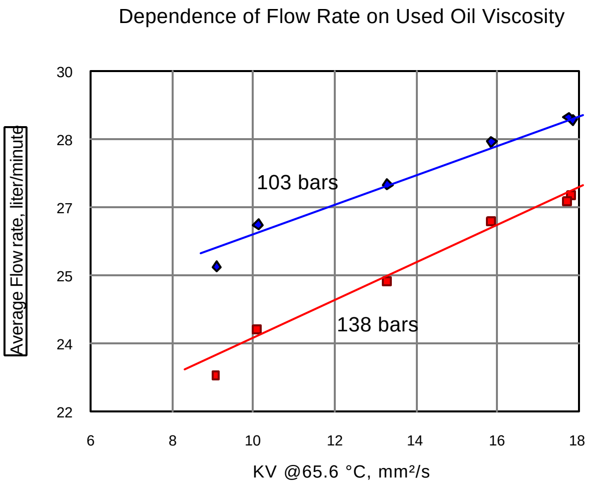
Flow rate data are reported in Table 4. Analysis of variance showed that at 99% confidence level, flow rate for any given fluid was independent of time even though some of the oils experienced a dramatic loss of kinematic viscosity.

Table 4: Flow Rate versus Time for the HSO Oils

		Flow Rate in liter/minute				
		Test time, hour				
Test Oil	Pressure, bar	0	25	50	75	100
HSO-01	103.4	29.07	28.92	28.92	28.92	28.92
HSO-02	103.4	27.52	27.52	27.52	27.44	27.56
HSO-03	103.4	26.61	26.72	26.50	26.91	26.46
HSO-04	103.4	25.66	25.74	25.78	25.78	25.48
HSO-05	103.4	29.07	28.92	28.84	28.84	29.34
HSO-06	103.4	28.54	28.43	28.50	28.50	28.39
HSO-01	137.9	27.18	27.29	27.29	27.25	27.22
HSO-02	137.9	25.25	25.36	25.51	25.02	25.59
HSO-03	137.9	24.34	24.42	24.34	24.15	24.30
HSO-04	137.9	22.83	23.32	23.47	23.36	23.36
HSO-05	137.9	27.44	27.06	26.99	27.03	27.03
HSO-06	137.9	26.42	26.50	27.22	26.69	26.65

It should be noted that, previous work indicated that initial flow rates were somewhat higher than the equilibrium values that were reached within 20 hours or less. The authors speculated that the use of different oil charges (5 versus 3 gallons), differences in break-in procedures, the use of different pumps (V104C versus V20) and improvement in temperature control may explain why the second study did not show any dependence of the flow rate on service time.

In figure 6, we plotted the flow rate at 138 and 103 bars as a function of the kinematic viscosity at 65.6 °C of the oils at the end of the 100 hour test (used oil viscosity).



Dependence of Flow Rate on Used Oil Viscosity

Figure 6: Dependence of Flow Rate on Used Oil Viscosity

Figure 6 shows that flow rate decreased almost in a linear manner when the used oil viscosity decreased. By linear regression we obtained the following least square equations:

Flow rate @ 103.4 bars= 22.81 + 0.350*KV @ 65.6 °C used, $R^2=.9774$

Flow rate @ 137.9 bars= 19.70 + 0.426*KV @ 65.6 °C used, $R^2=.9796$

These equations show that the rate at which flow rate decreases with used oil viscosity depends on the test pressure. The higher the pressure the more the flow rate depends on the used oil viscosity. However, despite the good coefficient of correlation, the rate at which flow rate decreases when decreasing the used oil viscosity accelerates when the used oil viscosity falls below 10 mm²/s. A similar trend can be observed in Figure 1.

This analysis led us to consider the use of the Poiseuille law to estimate the rate of leakage of the pump. We conducted a linear regression between flow rate and the ratio P/Viscosity at 65.6 °C. The viscosity data we used in this exercise are gathered in Appendix 2. Data at low shear rate were obtained by interpolation of the kinematic viscosity (ASTM D 445) at 40 and 100 °C. Viscosity at high shear rate was computed using data obtained at 100 and 150 °C at a shear rate of 10^6 s^{-1}.

We used the original pressure unit, psi, for this exercise and obtained the results shown in Table 5.

Table 5: Applicability of the Poiseuille Equation to Model Pump Leakage

Shear rate	Oil condition	Viscosity unit	Inter-cept	Slope	R²
Low	New	mm²/s	31.59	-0.0526	0.675
Low	Sheared	mm²/s	32.06	-0.0401	0.959
High	New	mPa.s	33.02	-0.0439	0.974
High	Sheared	mPa.s	32.61	-0.0376	0.975

The high coefficient of determination obtained in three of the four cases we investigated confirmed that the Poiseuille equation provides a reasonable estimate of pump leakage if viscosity is measured under appropriate conditions. This also confirms that the kinematic viscosity of the fresh oil cannot be used to estimate flow rate in service. On the other hand, selecting the kinematic viscosity of the used oil provides a significant improvement in the precision of the model. These data are shown in Figure 7. Further improvements can be obtained by considering the viscosity under high shear rate (10^6 s^{-1}).

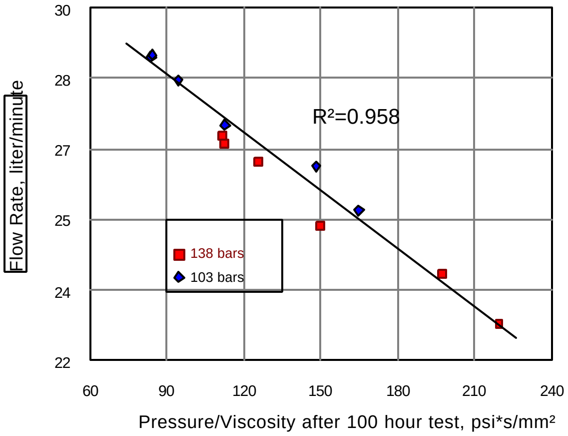


Figure 7: Flow Rate versus Pressure and Used Oil Viscosity (after 100 hour pump test)

This analysis confirmed the conclusions of the first study.

The authors also evaluated the ability of different shear test to simulate the shearing taking place in the vane pump loop after 100 hours at 138 bars. They found that the viscosity of the HSO oils after the 40 minutes Sonic test (ASTM 5621) were in excellent correlation with the used oil viscosity. The used oil viscosity after the sonic shear test were obtained by interpolating the results obtained at 40 and 100 °C. They are detailed in Appendix 2.

We used the viscosity after the Sonic test in the model discussed above and obtained the following least square equation.

Flow rate =
31.85 – 0.0394*P/(KV @65.6 °C after Sonic)
R²=0.948

The coefficient of determination is essentially identical to that obtained when using the oil viscosity at the end of the pump test, and a reasonable estimate of the performance of an oil in the vane pump test knowing its viscosity after shear in the Sonic test. The result is shown in Figure 8. This modeling approach has been proposed as a technique for calculating pump efficiency [5].

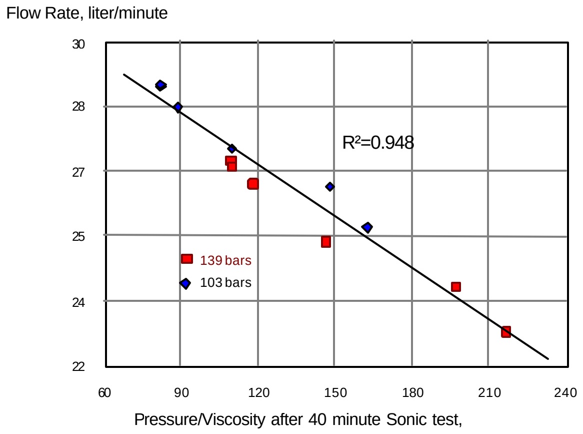


Figure 8: Flow Rate versus Pressure and Viscosity after the 40 Minute Sonic Test

REVIEW OF HIGH PRESSURE VANE PUMP DATA

In this hydraulic circuit, we used a Denison T6CM vane pump designed for mobile equipment. This pump can operate up to 250 bars on a continuous basis when using a proper lubricant. It is driven by a 15 kW electric motor at 1500 rpm. With the cartridge selected, this corresponds to a nominal flow rate of 31.9 liters per minute according to the pump manufacturer's data sheet.

DEPENDENCE OF PUMP PERFORMANCE ON PRESSURE AND TIME

The pump was operated for 300 hours according to the pressure cycle specified in the Denison TP 30283 procedure that is used to approve HF-0 oils. At the beginning of the test and then every 50 hours, the cycle was interrupted and the temperature of the test oil at the inlet of the pump was adjusted to about 80 °C using a heat exchanger located between the reservoir and the pump inlet. The oil after the throttle valve was cooled to about 85 °C using a second heat exchanger. After the temperature had stabilized, the flow rate was measured at 6 different pressures. Samples were taken every 50 hours and their kinematic viscosity (ASTM D 445) was measured at 40 and 100 °C.

For this work, we used an ISO 46 hydraulic fluid with a VI of 152 formulated with a shear stable polymer typical of the kind used to formulate a Denison HF 0 fluid. Inspection of the oil viscosity in Table 6 shows that only moderate viscosity loss takes place during the test. The viscosity loss is only about 5% after 300 hours under severe cycling conditions. This low shear level has to be contrasted with 11.8% viscosity loss after 20 hour in the KRL test on this fluid.

Table 6: Viscosity as a function of Time in the Denison T6CM Vane Pump

Time, h	KV 40°C mm²/s	% loss @40 °C	KV 100°C mm²/s	% loss @ 100 °C	V I
0	45.58	0.0	8.122	0.0	152
50	44.89	1.5	7.988	1.6	151
100	44.44	2.5	7.869	3.1	149
150	44.20	3.0	7.819	3.7	148
200	44.02	3.4	7.771	4.3	147
250	43.70	4.1	7.729	4.8	147
300	43.58	4.4	7.707	5.1	147

We plotted in Figure 9, the flow rate as a function of time for the six different pressures considered.

It can be seen that essentially no change of flow rate takes place during the entire 300 hour duration of the test. Analysis of variance confirmed that at 99% confidence interval, the flow rate was independent from test time. The fact that the flow rate does not decrease with test time in the high pressure vane pump further supports the observations made in the two medium pressure pumps.

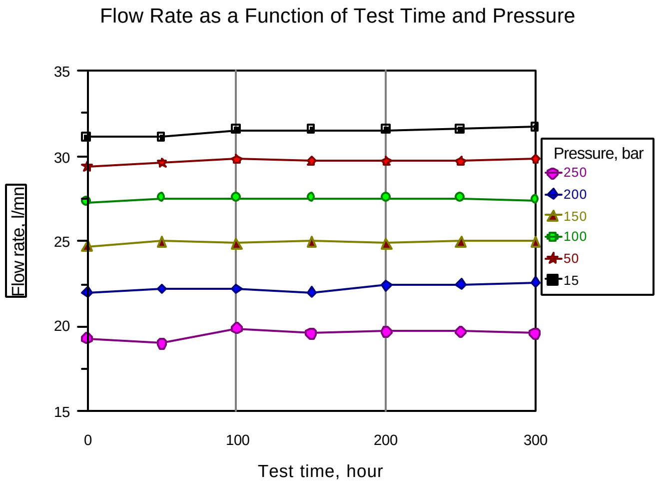


Figure 9: Flow Rate of Denison T6CM as a Function of Test Time and Pressure

SUMMARY

Results obtained in medium and high pressure vane pumps have been analyzed and enabled us to reach the following conclusions.

Observations from the Eaton-Vickers V104C vane pump results (Kopko, 1975):

- Flow rate of Newtonian oils depends on pressure and viscosity
- Flow rate of VI Improver containing oil at constant pressure changed only little with time despite the fact that some showed a large drop of their kinematic viscosity.
- The Poiseuille equation can be used to estimate the oil leakage using the oil viscosity at the end of the 100 hour test.
- The authors concluded that the viscosity seen by the pump is controlled by the sum of the permanent and temporary viscosity losses.

Observations from the Eaton-Vickers V20 vane pump results (Stambaugh, 1990):

- Flow rate of six VI Improver containing oils was essentially constant over extended testing.
- The Poiseuille equation again provided a good estimate of pump leakage provided viscosity was measured under high shear rate on the fresh or used oil or under low shear rate on the used oil. This confirmed findings from the first study on the role of permanent and temporary viscosity losses.

Observations from Denison T6CM vane pump results (current studies):

- The flow rate of a high VI oil did not change in service even after 300 hours of severe cycling conditions.
- The viscosity loss in extended service was much lower than that measured in the KRL 20 hour test.

CONCLUSIONS

- The kinematic viscosity of fresh oil does not provide a good basis to classify fluids according to their pumping efficiency in medium and high pressure vane pumps. Either the high shear rate viscosity of the fresh oil or used oil or the kinematic viscosity after the pump test can be utilized to rank oils according to their pumping efficiency.

- A shear test that correlates well with the sheared oil viscosity after extended service such as the Sonic test, thus serves as a useful basis for classifying oils according to their volumetric efficiency.

- The pump output of VI Improved oils will remain nearly constant for extended periods of time despite the fact that some of them may show a significant decrease of their kinematic viscosity.

- The use of a fluid formulated with a shear stable VI Improver will result in high and stable pumping efficiency at elevated temperature in medium and high pressure vane pumps.

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APPENDIX 1

PERMANENT SHEAR STABILITY OF VI IMPROVERS

Permanent shear stability index is defined as the percentage of polymer-contributed viscosity which is permanently lost due to shear. Expressed mathematically:

$$SSI_T = (\mu_i - \mu_f)/(\mu_i - \mu_o) \times 100\ \%$$

Where:

T = temperature at which viscosities are measured

μ_i= initial oil kinematic viscosity, mm^2/s

μ_f= final oil kinematic viscosity, mm^2/s

μ_o= kinematic viscosity of base oil blend, mm2/s (including all additives except VI improvers)

TEMPORARY SHEAR STABILITY OF VI IMPROVERS

The temporary shear stability of VI improvers can be defined by an index ($T\text{-}SSI_T$) which defines the percentage of polymer-contributed viscosity temporarily lost while the fluid is under stress. Expressed mathematically:

$$T\text{-}SSI_T = (\mu_{it} - \mu_{ft})/(\mu_{it} - \mu_o) \times 100\ \%$$

Where all the parameters are similar to those shown above, except that now where:

μ_{it}= kinematic viscosity at time of interest (t), mm^2/s

μ_{ft}= oil viscosity in mm^2/s, at a specified shear stress and time t

APPENDIX 2

Viscosity of HSO fluids at 65.6 °C

Equipment	Eaton-Vickers V20 vane pump				Sonic Test*
Test time, hours	0	0	100	100	0.666
Shear rate	Low	High	Low	High	Low
Unit	mm²/s	cP	mm²/s	cP	mm²/s
HSO-01	19.90	15.90	17.86	14.40	18.23
HSO-02	16.90	12.50	13.30	11.30	13.65
HSO-03	13.60	9.80	10.11	9.00	10.13
HSO-04	16.40	9.00	9.10	7.90	9.22
HSO-05	27.30	15.60	17.75	14.60	18.21
HSO-06	27.40	13.50	15.86	13.20	16.89

* ASTM D 5621