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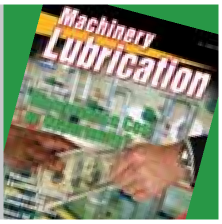

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The Benefits of Maximum Efficiency Hydraulic Fluids

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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 more demanding.

Viscosity variations associated with low starting temperature and high operating temperatures contribute to system efficiency and reliability losses in a variety of ways. Selection of the proper viscosity grade of hydraulic fluid is an important and cost-effective technique that allows equipment to start smoothly at low temperatures, and also deliver adequate oil flow rates needed for efficient operation at high temperatures.

This article discusses several techniques that enable the equipment user to identify the practical operating limits of a hydraulic fluid. This information can be used to determine the temperature operating window of a given fluid in a pump.

Fluid Selection

Viscosity is an important criterion in the selection of a hydraulic fluid. At low temperature, excessive viscosity may result in poor mechanical efficiency, difficulty in starting, and wear. As oil temperature increases, viscosity decreases, resulting in lower volumetric efficiency, overheating and wear. Pump and motor manufacturers often provide hydraulic fluid recommendations in their documentation covering:

- the maximum startup viscosity under load
- the range of optimum operating viscosity
- the maximum and minimum operating viscosity

Selection of the optimum fluid viscosity grade will provide the most efficient pump

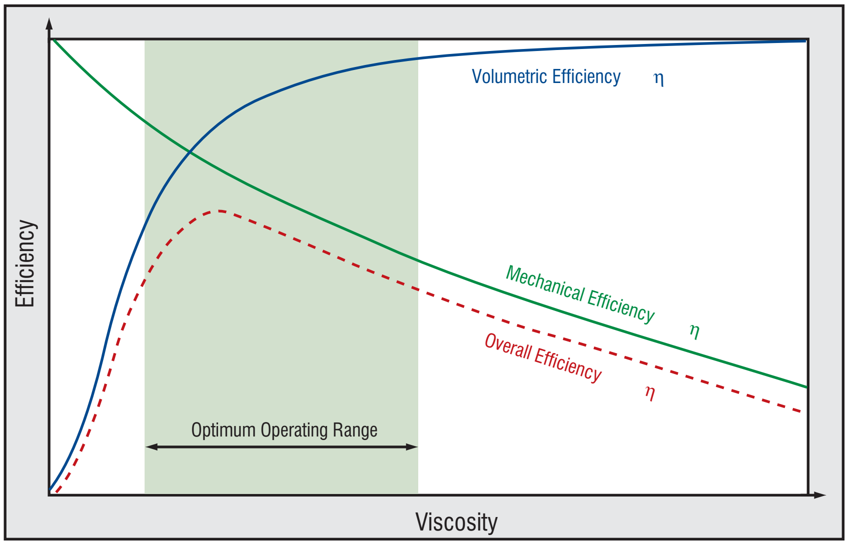

Figure 1. Relationship of Viscosity to Pump Efficiency

performance at standard operating temperatures, therefore minimizing lost time and energy and fuel costs for the operator.

Recent work by the authors has lead to the development of a new performance standard for hydraulic fluids, described as Maximum Efficiency Hydraulic Fluid (MEHF). MEHF fluids are formulated to provide a combination of high viscosity index and good shear stability, which enables all types of hydraulic pumps to deliver increased power at a lower level of energy consumption.

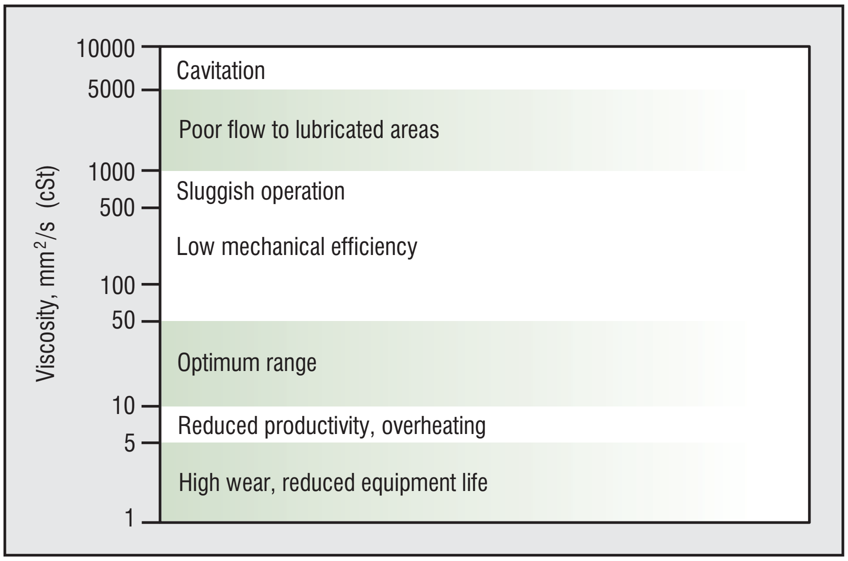

Figure 2. Fluid Viscosity vs. Performance

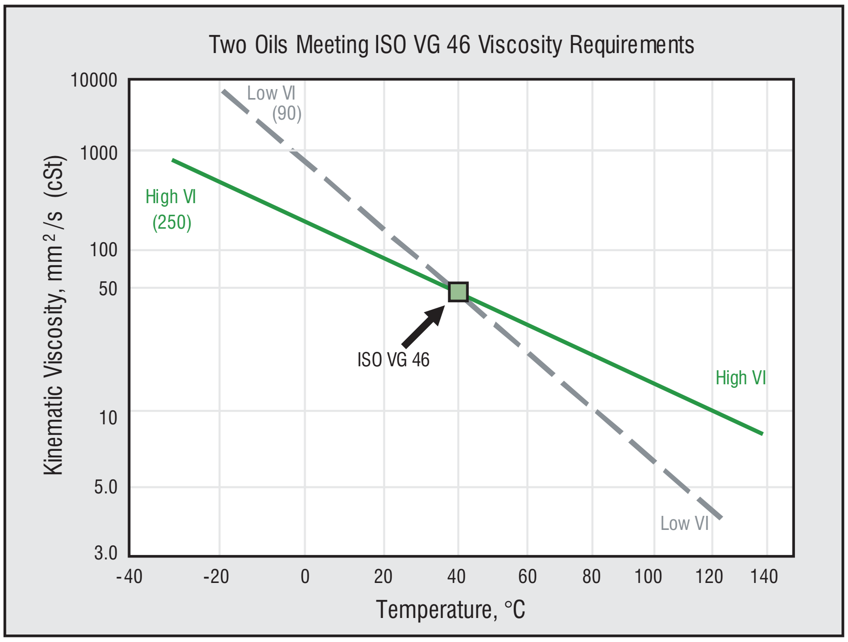

Figure 3. Viscosity-Temperature Relationship for Low and High VI Oils

Pump Efficiency

The performance of hydraulic pumps and motors is a critical factor in overall hydraulic system reliability. There are two elements of hydraulic efficiency: volumetric efficiency and hydromechanical efficiency. Hydromechanical efficiency relates to the frictional losses within a hydraulic component and the amount of energy required to generate fluid flow. Volumetric efficiency relates to the flow losses within a hydraulic component and the degree to which internal leakage occurs. Both of these properties are highly dependent on viscosity.

Hydromechanical efficiency decreases as fluid viscosity increases due to higher resistance to flow. Conversely, volumetric efficiency increases as fluid viscosity increases because of the reduction of the internal leakage. The overall efficiency of a hydraulic pump is the product of mechanical and volumetric efficiencies [Equation 1], and both factors must be considered simultaneously. As shown in Figure 1, there is a range of hydraulic fluid viscosity that optimizes the overall efficiency.

[Equation 1]

Overall efficiency = Hydromechanical efficiency * Volumetric efficiency

Cavitation, Wear and System Overheating

At low operating temperatures, high viscosity negatively affects the mechanical efficiency of the hydraulic system, resulting in reduced system performance, lubricant starvation and cavitation. Viscosity influences cavitation because high-viscosity fluids can create excessive pressure drop at the pump inlet. Cavitation causes metal fatigue and spalling which reduce pump life and generate abrasive metal particles in the fluid. Excessive viscosity from low-temperature conditions leads to pump starvation that may result in pump failure. Additionally, loss of the lubricating film creates high contact temperatures, excessive wear and ultimately results in pump seizure.

Consequently, pump manufacturers specify a maximum fluid viscosity limit at startup to ensure that cavitation is avoided. Improperly designed or undersized inlets and strainers aggravate the problems associated with high viscosity.

One of the essential functions of a hydraulic fluid is to provide a lubricating film that reduces wear on moving pump parts. Film effectiveness depends upon a balance between viscosity, sliding speeds and loads, and fluid stability within a hydraulic pump. As temperatures increase and the film thins, the lubricant film ruptures, allowing metal-to-metal contact, wear within the pump and additional fluid heating. Wear predominantly occurs in locations within a pump that are critical in terms of volumetric efficiency. Loss of volumetric efficiency causes the pump to work harder to produce the required flow. At the same time, high temperatures compromise volumetric efficiency as the result of low-viscosity fluid bypassing critical pump clearances. Thus, inadequate viscosity due to high temperatures creates a destructive cycle of rising temperatures, accelerated wear and increased internal leakage.

Multigrade Fluids Offer Improvement

Multigrade hydraulic fluids are often recommended for equipment where the operating temperatures can vary widely. High viscosity index (HVI) MEHFs enable efficient equipment operation over a wider temperature range than standard grade mineral oils. MEHF products are also recommended to eliminate seasonal oil changes, since a properly formulated multigrade performs adequately in both winter and summer temperatures.

MEHFs provide better low-temperature flow properties than an equivalent grade of single viscosity hydraulic oil at equivalent temperatures. While improved flow characteristics provide smoother operation and improved productivity, the primary performance advantage of an MEHF is its effectiveness in maintaining pumping efficiency at high temperatures. Pump internal leakage increases with increase in temperature and decrease in viscosity. A high VI fluid decreases at a lower rate than a standard single viscosity fluid, which contributes to less leakage and improved pump efficiency. The relationship of viscosity to temperature, and the viscometric advantages of high VI multigrade hydraulic fluids are shown in Figure 3.

Fluid Selection Techniques

A viscosity grade selection system aimed at supporting equipment users has been published by the NFPA, based on the recommendations of leading hydraulic pump manufacturers. Optimum viscosity grades are selected based on the concept of temperature operating window (TOW), which corresponds

	ISO Viscosity Grade					
Property	**VG 32**		**VG 46**		**VG 68**	
VI (the 200 VI fluids are MEHF products)	100	200	100	200	100	200
KV at 100°C, mm^2/s (cSt)	5.36	7.16	6.72	9.53	8.73	13.06
KV at 40°C, mm^2/s (cSt)	32.0	32.0	46.0	46.0	68.0	68.0
Temperature for 860 mm^2/s (cSt), °C	-7	-19	-2	-14	4	-8
KV at 100°C after 40 minutes Sonic, mm^2/s (cSt), ASTM D 5621	-	6.26	-	8.16	-	10.98
KV at 80°C after 40 minutes Sonic, mm^2/s (cSt), ASTM D 5621	-	9.07	-	12.19	-	16.84
KV at 40°C after 40 minutes Sonic, mm^2/s (cSt), ASTM D 5621	-	28.0	-	39.39	-	57.29
VI after 40 minute Sonic, ASTM D 5621	-	184	-	187	-	188
NFPA T2/13.13.2002 Grade	L32-32	L22-46	L46-46	L32-68	L68-68	L32-100

Table 1. Viscometric Properties of Test Oils

to the range of temperature where the oil viscosity provides acceptable performance in the pump (typically 13 to 860 mm²/s). Details on the use of the ALTOW system are given in NFPA Standard Practice T2.13.13-2002, available through the National Fluid Power Web site at www.nfpa.com.

Performance Advantage of High VI Oils

The most commonly used and widely available viscosity grades are ISO 32, 46 and 68. The following sections compare the performance of monograde (low-viscosity index) and multigrade (high-viscosity index) versions of these three fluids. It is important to recognize that shear stable fluids must be used in high-pressure hydraulic systems to achieve desirable performance. Fluids with low shear stability are commercially available, and are typically intended for use in low-pressure systems or for other applications such as automatic transmissions (ATF). The multigrade fluids selected for comparison in this work are intended for high-pressure hydraulic system service and have excellent shear stability, meeting the MEHF performance level definition. A description of these fluids can be found in Table 1. Consult your fluid supplier for guidance on the shear stability of its products to verify fluid performance claims.

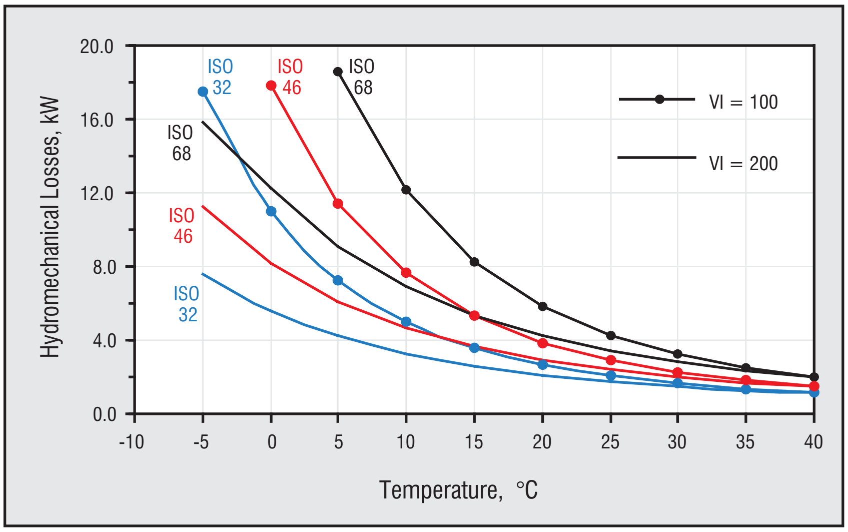

Figure 4. Hydromechanical Losses as a Function of Temperature, ISO Grade and VI

		Time Difference, percent		
Cartridge Size	Nominal Flow Rate ml/rev.	ISO 32	ISO 46	ISO 68
A	22	20.8%	15.5%	11.1%
B	34	9.2%	7.6%	6.0%
C	46	6.0%	5.2%	4.2%
D	70	3.6%	3.2%	2.6%

* Performance gains are based on used oil viscosity, after shear

Table 2. Additional Time Required for a 100 VI Fluid to Deliver the Same Volume as a 200 VI Fluid* at 80ºC, 200 bars and 2,000 rpm

Performance Advantage at Low Temperature

Calculations have been made on the additional energy, or hydromechanical losses (in kW), required to operate a mobile vane pump having a displacement of 10.8 ml/rev. at 800 rpm and 100 bars, conditions typical of those prevailing at startup. These data are shown in Figure 4.

Considering the example of ISO VG 46 fluids at 0°C, the data in Table 4 indicate that the monograde fluid requires 125 percent more energy (18 kW vs. 8 kW) than the MEHF to overcome the viscous drag.

The theoretical power input for the pump in this example is only 1.4 kW, assuming no hydromechanical energy losses take place (energy required to turn the rotor). Additional energy required to overcome the higher viscosity of the 100 VI fluids increases significantly at temperatures below 40°C, and dramatically below 0°C.

Performance Advantage at High Temperature

The authors have computed the actual flow rate and the total power requirement for vane pumps based on a given body, using four different-sized cartridges. Internal cartridge sets (rotors and vanes) are sized to deliver a specific flow rate by controlling the discharge volume per revolution. Calculations were made at a pressure of 200 bars, a speed of 2,000 rpm, and at two temperatures, 80°C and 100°C.

Flow Rate Advantage – Time Savings

Knowing the actual flow rate Q_a, one can determine the time needed to fill a given linear motor of volume, V. A linear motor is typically a hydraulic cylinder that fills with fluid, displacing a rod that delivers motion under load.

[Equation 2]

$$\text{Time} = V/Q_a$$

By calculating the ratio of the time required for two oils having the same ISO VG grade but different VI, one can estimate the time advantage for the high VI oil to deliver the same volume of fluid. In this work, the authors used the viscosity of the high VI oils after the Sonic 40-minute shear test to compute the actual flow rate (Table 1). This represents a good estimate of the used oil viscosity in a 2,000 psi vane or piston pump system.

[Equation 3]

$$\text{Time}_{(VI=100)}/\text{Time}_{(VI=200)} = Q_{a(VI=200)}/Q_{a(VI=100)}$$

The benefit offered by the high VI oils decreases when increasing the cartridge size and increasing the ISO grade. This is because the larger the cartridge, the lower the internal leakage relative to the pump flow rate.

Field studies showed that peak operating temperatures in mobile hydraulic equipment often exceed 100°C. Therefore, the flow rates in this series of pumps at this higher temperature were also calculated. The data in Table 4 indicate that the high VI fluids at 100°C deliver between five to 30 percent greater flow rate, allowing a cylinder to fill more quickly.

Comparing the data at 80°C to the data at 100°C, one can see that high VI fluids show an even greater advantage as fluid temperatures increase above 80°C.

Efficiency Advantage – Cost Savings

Knowing the total power required to deliver the hydraulic power and to overcome the hydro-mechanical losses, one can determine the energy needed to fill the linear motor of volume V.

[Equation 4]

$$\text{Energy} = \text{Total Power} * \text{Time}$$

The authors calculated the power needed to drive the pump at 80°C and 100°C, using fluids

		Time Difference, percent		
Cartridge Size	Nominal Flow Rate ml/rev.	ISO 32	ISO 46	ISO 68
A	22	x	x	30.4%
B	34	22.5%	17.9%	13.8%
C	46	13.2%	11.3%	9.2%
D	70	7.2%	6.4%	5.4%

* Performance gains are based on used oil viscosity, after shear

Table 3. Additional Time Required for a 100 VI Fluid to Deliver Same Volume as a 200 VI Fluid* at 100°C, 200 bars and 2,000 rpm

		Energy Savings, percent		
Cartridge Size	Nominal Flow Rate ml/rev.	ISO 32	ISO 46	ISO 68
A	22	20.0%	14.6%	9.0%
B	34	8.3%	6.8%	4.7%
C	46	5.7%	4.6%	3.2%
D	70	3.3%	2.7%	2.0%

* Performance gains are based on used oil viscosity, after shear

Table 4. Energy Savings with High VI Oils* at 80°C to Deliver Same Volume (200 bars, 2,000 rpm)

		Energy Savings, percent		
Cartridge Size	Nominal Flow Rate ml/rev.	ISO 32	ISO 46	ISO 68
A	22	x	x	27.9%
B	34	22.0%	17.4%	12.9%
C	46	12.8%	11.0%	8.5%
D	70	6.9%	6.2%	5.0%

* Performance gains are based on used oil viscosity, after shear

x Data not reported because the volumetric efficiency for the 100 VI oils ISO 32 and 46 was lower than 50 percent.

Table 5. Energy Savings with High VI Oils* at 100°C to Deliver Same Volume

with different VIs. This allowed them to determine the difference in energy required to deliver the same volume of fluid under a given pressure and pump speed.

[Equation 5]

$$\text{Energy}_{(VI=100)}/\text{Energy}_{(VI=200)} = \text{Power}_{(VI=100)} {}^{*}Q_{a\ (VI=200)}/(\text{Power}_{(VI=200)} {}^{*}Q_{a(VI=100)})$$

The data in Table 4 indicate that the high VI multigrade fluid at 80°C, 200 bars and 2,000 rpm may save between two and 20 percent in energy consumption over the 100 VI fluid.

Similar to the approach taken in the Flow Rate Advantage section, the authors also calculated energy consumption at 100°C, to identify the potential energy savings at a temperature closer to a typical peak operating temperature. The data in Table 5 indicate that the high VI fluid at 100°C, 200 bars and 2,000 rpm may save between five and 28 percent in energy consumption.

As fluid temperature increases, the energy savings attributed to the high VI fluids is amplified.

Pump	A	B	C	D
kW	15.5	24.0	31.9	48.1
Gallons of Diesel Fuel Used	2,141	3,316	4,407	6,645
Gallons of Diesel Fuel Saved	313	224	201	182
Annual $ Saved	$ 563	$ 403	$ 362	$ 328

Assumptions: 8 hours/day, 250 days/year, diesel fuel in USA at $1.80/gallon
Cost savings for 200 VI MEHF 46 grade fluid vs. monograde fluid.

Table 6. Fuel and Cost Savings - Single Mobile Vane Pump at 200 bar, 2,000 rpm, 80°C

Pump	A	B	C	D
kW	15.5	24.0	31.9	48.1
Gallons of Diesel Saved	37,557	26,888	24,108	21,797
Annual $ Saved	$ 67,603	$ 48,398	$ 43,394	$ 39,235

Assumptions: 8 hours/day, 150 days/year, diesel fuel in USA at $1.80/gallon
Cost savings for 200 VI MEHF 46 grade fluid vs. monograde fluid.

Table 7. Fuel and Cost Savings - Construction Equipment Fleet - 100 Units [200 Mobile Vane Pumps at 200 bar, 2,000 rpm, 80°C]

Conclusion

Cost savings for specific applications can be calculated based on the data. The cost savings associated with the use of maximum efficiency hydraulic fluids in a single vane pump are approximately $400 per year per pump. This advantage could be expected to result in approximately $50,000 savings annually for a medium-sized equipment fleet (250 assets).

Space did not allow for a detailed example to be printed in these pages. However, an example of a detailed analysis can be found by searching for the article title at www.machinerylubrication.com.

Relative Operational Cost Comparisons

The relative energy savings data presented in this article can be used to generate cost-saving estimates for specific applications. Consider the case of a single mobile vane pump running at typical mobile construction equipment operating conditions of 200 bar, 2,000 rpm, and 80°C. Depending on the particular pump size, the potential diesel fuel savings range from 200 to 300 gallons per year. Cost saving calculations can be made using the following formula:

[Equation 6]

Total fuel consumption (liters) =
Pump power requirement (kW) *
Hours of pump operation (hours) *
Diesel fuel consumption rate (0.22 kg/kWh) *
Density of diesel fuel (1.19 liters/kg)

[Equation 7]

Fuel savings (liters) = Total fuel consumption * Relative energy savings (percent from Tables 4 and 5)

[Equation 8]

Cost savings = Fuel Savings * Local cost of diesel fuel

Fuel and cost savings calculations for an ISO 46 hydraulic fluid in a single pump and a medium-sized construction equipment fleet are presented in Tables 6 and 7.

The comparison of the performance at low and high temperature of six hydraulic fluids with three different ISO grades (VG 32, 46 and 68) and two different Viscosity Indices (100 and 200) demonstrated the following conclusions:

The high VI oils that meet the MEHF performance level definition contributed to significantly lower hydromechanical losses at temperatures lower than 40°C. The gain in hydromechanical efficiency can exceed 50 percent at start-up temperature, resulting in lower energy consumption, shorter warm-up times and reduced wear.

At temperatures of 80°C and 100°C, calculations made for a series of vane pumps showed that the high VI oils deliver a higher flow rate and a better overall efficiency. This translates into higher equipment productivity, as well as significantly lower operating costs for the equipment user due to lower fuel consumption. Energy and fuel savings up to 20 percent can be expected under standard operating conditions when MEHF-type oils are used. Higher productivity gains and savings can be achieved at peak operating temperatures.

The cost savings associated with the use of maximum efficiency hydraulic fluids in a single vane pump are approximately $400 per year per pump. This advantage could be expected to result in approximately $50,000 savings annually for a medium-sized equipment fleet.

Editor's Note:

This work was presented at the Lubrication and Fluid Power Expo in Indianapolis, May 4-8, 2003. This article with complete references and more detailed analysis can be found online at www.machinerylubrication.com.

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