IMPROVING PUMP EFFICIENCY AND SYSTEM PERFORMANCE BY SELECTING THE OPTIMUM FLUID VISCOSITY GRADE

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ABSTRACT

Hard working hydraulic equipment must frequently operate at temperature extremes, which can negatively impact system response and reduce equipment life. Low temperature start-up with a high viscosity fluid may lead to sluggish operation, high hydro-mechanical losses, and pump cavitation. At peak operating temperature the fluid viscosity may be too low, resulting in poor pump volumetric efficiency, and system overheating.

To help end-users select the appropriate fluid, the National Fluid Power Association (NFPA) has published a recommended practice entitled "Viscosity Selection Criteria for Hydraulic Motors and Pumps". This practice describes a technique for determining the high and low temperature grade of an oil that would provide adequate lubrication.

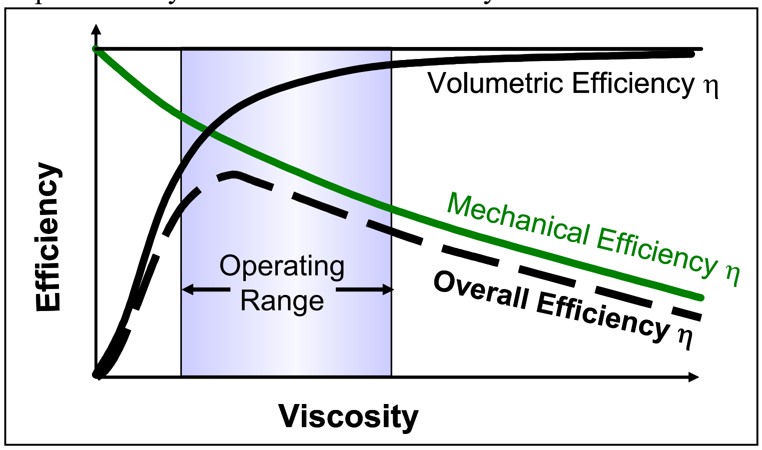
This presentation will review the fundamentals of pump efficiency, highlight the role of the hydraulic fluid in system performance, and review the ability of four major viscosity classification systems, including the NFPA practice and the Swedish Standard SS 155434 (Edition 4), in helping an equipment user maximize hydraulic system efficiency over a range of temperature.

KEYWORDS: Hydraulic Fluid, Pump Efficiency, Viscosity Grade, Swedish Standard, NFPA, TOW, ALTOW.

1 EFFECT OF VISCOSITY ON PUMP EFFICIENCY

Viscosity is one of the most important criteria in the selection of a hydraulic fluid. At low temperature, excessive viscosity will result in poor mechanical efficiency. At high temperature, low viscosity will result in low volumetric efficiency [1]. Figure 1 shows the dependence of pump efficiency on hydraulic fluid viscosity.

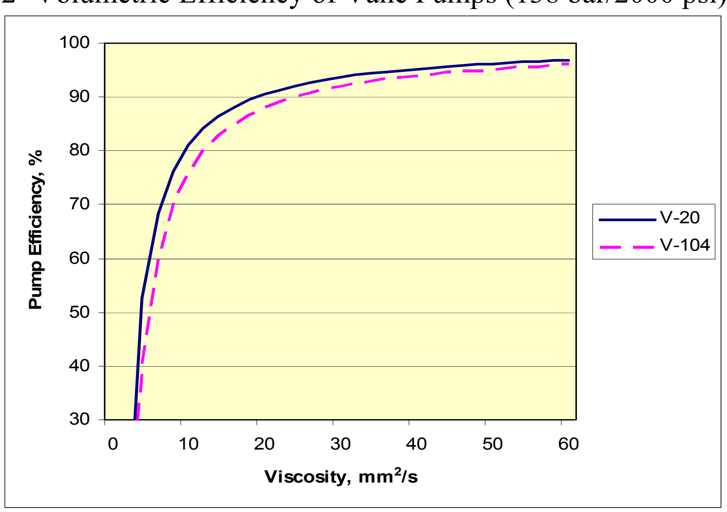
Figure 1- Pump Efficiency as a function of Viscosity



Selection of an appropriate hydraulic fluid is a challenging task for the equipment operator. In this process, one must consider the range of temperature experienced by the lubricant. This range corresponds to the "Temperature Operating Window" (TOW) of the hydraulic fluid, in which its viscosity must remain within the minimum and maximum values specified by the equipment manufacturer.

Work completed in vane pumps [2] enabled us to determine the dependence of volumetric efficiency on viscosity and pressure. We plotted in Figure 2 the volumetric efficiency versus viscosity for the Eaton-Vickers V20 and V104C pumps at 138 bars (2000 psi). The pump efficiency drops quickly when the fluid viscosity falls below the lowest optimum value of 13 mm^2/s recommended by the OEM.

Figure 2- Volumetric Efficiency of Vane Pumps (138 bar/2000 psi)



2 REVIEW OF VISCOSITY CLASSIFICATION AND SPECIFICATION SYSTEMS

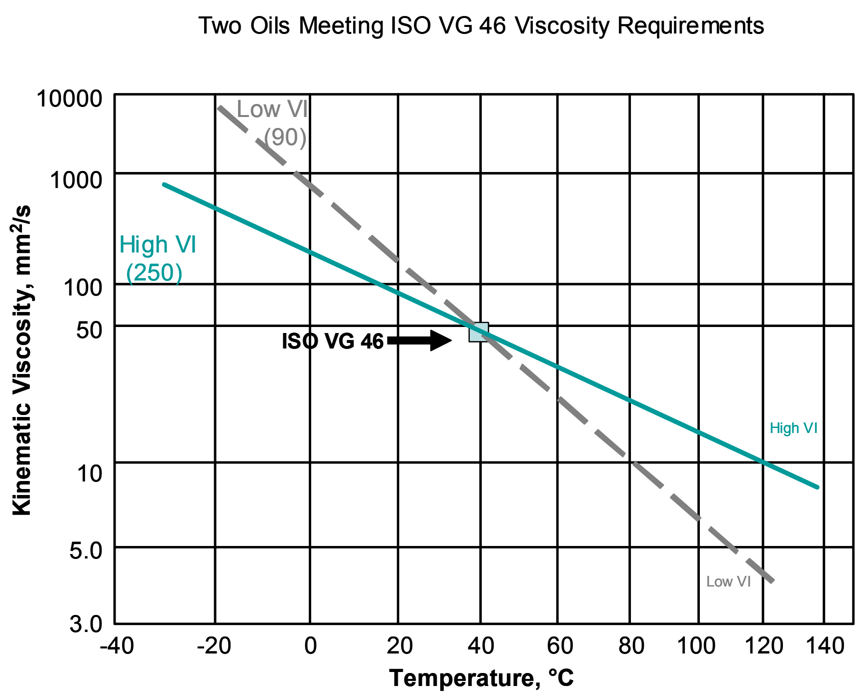
Several viscosity classification systems are currently in use. They were designed to provide lubricant suppliers, users, and equipment manufacturers a common, meaningful basis for specifying and selecting lubricants. In this section we will review four of the most important systems.

2.1 ISO 3448 (ASTM D 2422)

In the mid-seventies, a co-operative effort between ASTM, ASLE, BSI, and DIN resulted in the ISO 3448 Viscosity Classification for Industrial Liquid Lubricants [3]. It was designed to cover the entire range of kinematic viscosities of liquid lubricants using a limited numbers of discontinuous grades. The viscosity grade width was set to be 10% on either side of the mid-point value to simplify engineering design calculations. The grades were defined on the basis of the fluid viscosity at 40 °C. This temperature was selected because it was close to the average service temperature experienced by industrial hydraulic equipment at that time.

The ISO classification system works well for hydraulic fluids which do not contain a viscosity index (VI) improver. For oils with a VI (ASTM D 2270) ranging between 90 and 105, there is no overlap between grades when the temperature lies between -20 and 100 °C [4]. However, the system is of limited value when high VI oils are considered. In this case, oils having the same ISO grade but different viscosity indices have different viscosities at low and high temperatures and thus different performance in service. This point is illustrated in Figure 3.

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



2.2 ASTM D 6080.

In the 1980's, an effort was initiated by ASTM to develop a better, more informative classification system. This culminated in 1997 with the approval of ASTM D 6080. The objective was to have a common, meaningful basis for classifying lubricants derived from viscosities measured by test methods which have a direct relationship to hydraulic fluid performance. This practice was not intended to replace ISO 3448. Rather, it was an enhancement intended to provide a better description of the viscosity characteristics of lubricants used as hydraulic fluids [5]. It includes factors related to low temperature viscosity, high temperature viscosity, and shear stability, which improve its relevance to actual in-service performance of hydraulic fluids.

2.2.1 Low Temperature Viscosity Grades

Ten Low Temperature Viscosity Grades are defined by ASTM D 6080. They are based on the temperature at which the oil reaches a viscosity of 750 mPa.s measured in the Brookfield viscometer (ASTM D 2983). This value corresponds to the maximum start-up viscosity specified by several OEM's for vane pumps. The limits for the low temperature grades are shown in Table 2.

Table 2: Low Temperature Viscosity Grades according to ASTM D 6080.

	Temperature, °C, for Brookfield viscosity of 750 mPa.s	
Viscosity Grade	Minimum	Maximum
L5	-	-50
L7	-49	-42
L10	-41	-33
L15	-32	-23
L22	-22	-15
L32	-14	-8
L46	-7	-2
L68	-1	4
L100	5	10
L150	11	16

2.2.2 Shear Stability and Viscosity Index (VI)

ASTM D 6080 includes a high temperature viscosity designation of the fluid corresponding to its rounded kinematic viscosity at 40 °C (ASTM D 445) after it has been sheared in the 40 minute Sonic test (ASTM D 5621).

For fluids containing a viscosity index improver, the new viscosity classification also includes a viscosity index designation (ASTM D 2270) after shearing the fluid in the 40 minute Sonic test.

2.2.3 ASTM D 6080 Hydraulic fluid designation

The designation of fluids according to ASTM D 6080 is as follows:

General: ISO VG xx Lyy-zz (VI)	Example: ISO VG 46 L32-42 (170)

- xx is the fresh oil viscosity grade as per ISO 3448 (ASTM D 2422)
- Lyy is the low temperature grade based on the temperature at which the fresh oil viscosity reaches 750 mPa.s (Table 2)
- zz is the viscosity at 40 °C after shearing in ASTM D 5621
- VI is the viscosity index as per ASTM D 2270 after shearing in the Sonic test ASTM D 5621.

2.3 NFPA Recommended Practice: "Viscosity Selection Criteria for Hydraulic Motors and Pumps." NFPA/T2.13.13-2002

In April 2002, the USA based National Fluid Power Association (NFPA) published a document entitled "Viscosity Selection Criteria for Hydraulic Motors and Pumps" [1]. In order to design this practice, a large number of hydraulic component manufacturers were surveyed regarding the minimum and maximum viscosity that their equipment will tolerate.

Using the information supplied by the OEM's, and knowing the minimum start-up and peak operating temperature, the end-user can utilize either the TOW (Temperature Operating Window) or ALTOW (ALternative TOW) methods to determine an optimum fluid viscosity grade for their application.

2.3.1 Low Temperature Viscosity Grade

The low temperature viscosity grades are defined in the same manner as described in ASTM D 6080. Each low temperature viscosity grade corresponds to a range of temperature at which a viscosity of 860 mm^2/s (approximately 750 mPa.s) is reached.

2.3.2 High Temperature Viscosity Grade

The high temperature viscosity grades were defined at 100 ºC by extrapolating the viscosity at 40 ºC of oils having a VI of 100. The minimum of the NFPA high temperature grade corresponds to the mid-point of the corresponding ISO grade, and the maximum of the NFPA grade to the mid-point of the next higher ISO grade. The limits for the high temperature viscosity grades defined by the NFPA practice are given in Table 3.

Table 3: Definition of NFPA High Temperature Grade

NFPA High Temperature Grade	KV 100 ºC minimum, mm^2/s	KV 100 ºC maximum, mm^2/s
15	2.6	<3.4
22	3.4	<4.3
32	4.3	<5.4
46	5.4	<6.7
68	6.7	<8.7
100	8.7	<11.4

2.3.3 NFPA Hydraulic fluid designation

The designation of fluids according to NFPA/T2.13.13-2002 is as follows:

General: Lyy-hh	Example: L32-46

- Lyy is the low temperature grade based on the temperature at which the fresh oil viscosity reaches 750 mPa.s (Table 2)
- hh is the high temperature viscosity grade at 100 °C according to Table 3.

2.4 Swedish Standard SS 15 54 34 (Edition 4)

This standard includes a comprehensive set of viscosity and performance requirements. In particular, it defines three viscosity grades (32, 46, 68). The "M" grades are intended for indoor applications where start-up temperatures remain above freezing. The "V" grades are designed for use in outdoor equipment that can be subjected to low ambient temperatures. The V grades are defined by their viscosity at 40 ºC, and by a maximum viscosity at low temperature that depends on the grade. Each V grade also includes a shear stability requirement after the 20 hour KRL test. The viscometric requirements for each of the three V grades are shown in Table 4.

Table 4:
Swedish Standard SS 15 54 34 (Edition 4) Viscometric Requirements (V Grades)

Property	V32	V46	V68
KV 40 ºC, mm2/s	28.8 – 39.0	>39.0 – 57.0	> 57.0 – 74.8
KV -20 ºC, mm2/s After 72 hr	---	<=2400	<=5000
KV -30 ºC, mm2/s After 72 hr	<=4000	---	---
KV 100 ºC, mm2/s After 20 hr KRL	>4.5	>6.0	>7.0

The complete oil designation specifies an extensive number of performance properties, such as antiwear, foaming and air release, anti-corrosion, demulsibility and filterability. The fluid grade naming convention also requires the rating of its oxidative stability and environmental acceptability. Three levels of oxidative stability requirements are specified in order to accommodate a broad range of fluid base oil composition (mineral oil, synthetic, and biodegradable fluid types).

2.4.1 High Temperature Viscosity Grade

Oils are classified according to their kinematic viscosity at 40 ºC, as well as their viscosity at 100 ºC after shear. The minimum and maximum of each grade at 40 ºC is different to that specified by ISO 3448. Grades are wider and the scale is continuous.

2.4.2 Low Temperature Requirements

For each V grade, there is a low temperature requirement expressed as a maximum kinematic viscosity after 72 hours of soaking at the designated test temperature (-20 ºC or -30 ºC). This extended soaking is intended to promote the formation of wax crystals that could increase the fluid viscosity.

2.4.2 Shear Stability

For each grade, the specification includes a minimum viscosity at 100 ºC after the KRL 20 hour shear test (CEC-L-45-T-93).

3 COMPARISON OF INFORMATION PROVIDED BY THE FOUR VISCOSITY SYSTEMS

A review of the four viscosity systems shows that they provide different types of information that can be used to facilitate the selection of an appropriate grade of hydraulic fluid.

The ISO classification system provides a minimum level of information concerning the fluid viscosity. It only enables the user to rank oils according to their viscosity at 40 ºC.

ASTM D 6080 was developed to address the shortfalls of the ISO classification by providing information on, a) the viscometric properties of a fluid at both low and high temperature and, b) its ability to maintain its viscosity after extended service. This system introduced low temperature viscosity grading (L grades) as part of the designation. Despite being highly informative, this complex system has not yet gained wide industry acceptance.

The NFPA recommended practice builds on ASTM D 6080 for the definition of the low temperature grades. It is also the first system that provides guidance on the selection of the optimum viscosity grade required to satisfy the OEM requirements for their equipment. It does so by taking into account the minimum and maximum viscosity requirements at peak and start-up temperatures respectively. The NFPA system does not specifically include a shear stability requirement, but makes reference to ASTM D 6080.

The “V” grades defined by the Swedish standard are specifically designed for use in outdoor applications and include a more severe shear stability test and more stringent low temperature requirements than ASTM D 6080. The KRL 20 hour test included in the Swedish standard is significantly more severe than the Sonic 40 minute test used in ASTM D 6080 [6]. This is especially relevant for the higher viscosity grades. The determination of the low temperature viscosity according to the Swedish Standards includes a 72 hour soaking period versus only 16 hours for the Brookfield test for ASTM D 6080 and the NFPA recommended practice. However, unlike the NFPA practice, the "V" grades do not enable the end-user to easily select the most appropriate viscosity grade that would provide optimum equipment performance over a specific range of operating temperatures.

Appendix 1 provides an overview of the viscometric requirements of the four viscosity systems.

4 EXAMPLE OF THE USE OF THE SWEDISH STANDARDS AND OF THE NFPA CLASSIFICATIONS

In order to compare the two classification systems, we have considered three formulations that fully comply with the "V" viscosity grades defined by the Swedish Standards. Table 5 shows the main viscosity characteristics of these fluids.

Table 5: Viscosity of Oils Formulated According to SS 155 54 34

Swedish Standard Grade	**V32**	**V46**	**V68**
KV 40 ºC, mm^2/s	31.5	44.2	67.9
KV 100 ºC, mm^2/s	7.48	9.05	12.30
Viscosity Index (fresh oil)	216	192	181
KV 100 ºC after KRL 20 hr, mm^2/s	5.11	6.27	7.75
KV 100 ºC after 40 minute Sonic, mm^2/s	5.21	6.66	8.86
KV -20 ºC after 72 hr of soaking, mm^2/s		2115	4805
KV -30 ºC after 72 hr of soaking, mm^2/s	3420		
Temperature for 860 mm^2/s *	-21	-13	-6

* based on extrapolated viscosity at 40 and 100 ºC.

To define the high temperature grade of these three oils according to the NFPA practice, we have considered their viscosity at 100 ºC after the 40 minute Sonic test. In order to determine their L grade, we extrapolated their viscosity at 40 and 100 ºC to estimate the temperature at which they would reach a viscosity of 860 mm^2/s. Using these estimates, we obtained the following grading according to the four viscosity systems. They are detailed in Table 6.

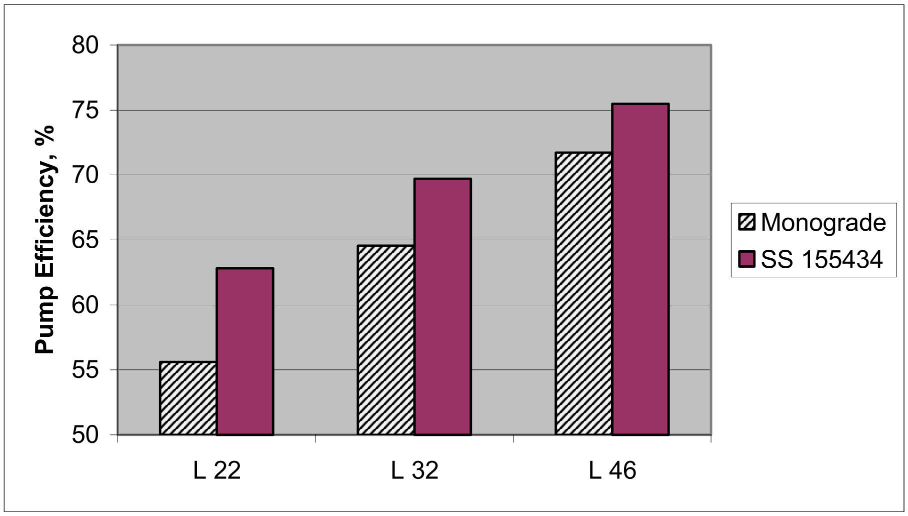
Table 6: Comparison of the Four Viscosity Grading Systems

Swedish Standard Grade	V32	V46	V68
NFPA Grading	L22-32	L32-46	L46-100
ASTM D 6080 Grading	VG 32 L22-22 (170)	VG 46 L32-33 (160)	VG 68 L46-51 (160)
ISO 3448 Grading	VG 32	VG 46	VG 68

It can be seen that, according to the NFPA practice, oils satisfying the Swedish standards are multigrades, even after severe shearing in the 40 minute Sonic test.

While these three oils provide outstanding performance at low temperature, we also wanted to evaluate the benefit they can provide at high operating temperature. For this purpose, we have compared the volumetric efficiency at 100 ºC and 138 bars (2000 psi) in the Eaton-Vickers V-20 [2] of three monograde oils that provide equivalent low temperature performance to that of the three multigrade oils described above after shearing in the KRL 20 hour test. The results of this exercise are shown in Figure 4.

Figure 4:
Volumetric Efficiency in the Eaton-Vickers V-20 pump of oil having the same L Grade



This chart shows that the three oils meeting the viscometric requirements of the V32, V46 and V68 grades provide an improvement in volumetric efficiency between 5 and 13%, compared to monograde oils having the same L grade. These estimates are made for an Eaton-Vickers V-20 pump operating at 100 ºC and 138 bars (2000 psi).

5 CONCLUSIONS.

An analysis of four of the most widely used viscosity classification systems was conducted to understand their viscometric requirements at both low and high temperature. This evaluation showed that these systems provide different levels of information on the ability of a hydraulic fluid to perform satisfactorily over a specific range of temperatures.

High temperature grades are defined by a range of viscosity at 40 ºC in the ISO, the ASTM and the Swedish Standards. The NFPA practice and the Swedish Standard both use a range of viscosity at 100 ºC to define high temperature grades. This temperature is closer to the peak operating temperature encountered in modern mobile hydraulic equipment.

In the ASTM D 6080 Standard and in the NFPA practice, the low temperature viscosity grades are defined by a range of temperature at which the oil reaches a viscosity of 750 mPa.s (860 mm^2/s) in the Brookfield test. There is no requirement at low temperature in the ISO classification. The Swedish Standards for the “V” grades include a maximum kinematic viscosity requirement that is measured after 72 hours of cold soaking.

The V grades defined by Swedish Standards SS 155434 (edition 4) are widely used in Europe. They provide satisfactory performance over a wide range of operating temperatures (TOW). They include a shear stability and a low temperature viscosity requirement that are more severe than those included in ASTM D 6080.

The Swedish Standards differ significantly from the ISO system and cannot be easily compared to the ASTM D 6080 Standard or to the NFPA practice. However, using the extrapolated temperature at which fluids meeting the Swedish Standards would reach 860 mm^2/s and the viscosity at 100 ºC after the 40 minute Sonic test, one can determine their low and high temperature grades according to the NFPA practice.

Three typical hydraulic oils meeting all the viscometric requirements for the "V" grades of the Swedish Standards were considered in this paper. They are characterized by very high viscosity indices, and can be classified as multigrade oils according to the ALTOW procedure of the NFPA recommended practice. The combination of outstanding low temperature performance and ability to retain their viscosity at high temperature enable these lubricants to provide improved volumetric efficiency at high operating temperature (100 ºC) compared to monograde oils offering the same low temperature performance (same L grade).

We estimated that the three oils considered that satisfied the Swedish Standard could provide an average 9% improvement in volumetric efficiency compared to monograde oils having the same L grade.

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APPENDIX 1- Summary of the Four Viscosity Classification System Requirements

Viscosity System	High Temperature Grade Definition		Low Temperature Grade Definition		Shear Stability Requirements		
	KV 40 ºC	**KV 100 ºC**	**Method**	**Requirement**	**Method**	**Requirement 1**	**Requirement 2**
ISO 3448 ASTM D 2422	Range, mm^2/s ASTM D 445 ± 10% of mid-point						
ASTM D 6080	Range, ASTM D 2422 mm^2/s		Brookfiel d, ASTM D2983, 16 hr cold soak	Temperature for 750 mPa.s viscosity	40 minute Sonic, ASTM D 5621	Report KV 40 ºC mm^2/s	Report VI
Swedish Standard 15 54 34 Edition 4	Range, mm^2/s	Minimum viscosity after shear, mm^2/s	Capillary, ASTM D 445, -20 or -30 ºC	Maximum viscosity after 72 hour cold soak	20 hour KRL, CEC-L-45-T-93	KV 100 ºC, Meet minimum viscosity spec., mm^2/s	
NFPA T2.13.13-2002		Range, mm^2/s	Brookfiel d ASTM D2983, 16 hr cold soak	Temperature for 750 mPa.s (860 mm^2/s) viscosity			