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IMPACT OF FRESH AND SHEARED OIL VISCOSITY REQUIREMENTS ON THE FORMULATION OF HYDRAULIC FLUIDS

Abstract

For many years hydraulic oils were selected using the ISO 3448 viscosity classification. Developed in the mid-seventies, it defines a finite number of discontinuous grades based on a minimum and maximum viscosity at 40 °C. In 1997, efforts by ASTM resulted in the ASTM D 6080-97 classification that included several viscosity requirements on the fresh and sheared oil. More recently, two new sets of viscosity and VI limits on the fresh and sheared oil were proposed to provide improved equipment efficiency compared to conventional HM oils. These are the Maximum Efficiency Hydraulic Fluid definition (MEHF) and the National Fluid Power Association (NFPA) guidelines for hydraulic fluid viscosity selection.

Any additional viscometric requirement to the ISO grade definition introduces new constraints on both the kinematic viscosity and VI of the formulation. Using a large number of blends based on VI Improvers having a different shear stability level, we investigated the impact of the viscosity constraints included in the MEHF and NFPA guidelines on the formulation windows of the three most common ISO grades. The degree to which the guidelines overlap, the so-called "formulation window" was found to depend on the ISO grade and shear stability of the VI Improver considered. This work provides a framework for an improved ability to select formulation targets considering these new guidelines.

1. Hydraulic fluid classification and selection guidelines

Several viscosity classifications and selection guidelines for hydraulic fluids are currently in use globally. They were designed to provide lubricant suppliers, users and equipment manufacturers a common, meaningful basis for specifying and selecting lubricants for use. These systems range from the simple ISO 3448 Viscosity Classification, which classifies oils based only on their viscosity at 40 °C, to the more complex ASTM D 6080-97 [1] that classifies oils according to their viscosities at several temperatures, VI and shear stability. In 2002, the NFPA T2.13.13-2002 [2] recognized the need to classify oils according to their viscosity at

100 °C since it is closer to the peak oil temperature encountered in mobile hydraulic equipment. It defines a process for selecting hydraulic fluids based on the requirements of major pump manufacturers and the range of temperature to which the fluid is exposed. At low temperature, it uses the definition of the L grade first introduced in the ASTM D 6080-97 classification.

Since the introduction of the NFPA Recommended Practice in 2002, two areas of improvement have come up; shear stability and energy efficiency.

1.1) Accounting for shear stability

The 2002 NFPA Recommended Practice did not take into consideration the shearing of Viscosity Index Improvers (VIIs) used to formulate high VI hydraulic fluids in service that results in a loss of viscosity.

Table 1: NFPA High Temperature Viscosity Grades

	Kinematic viscosity at 100 °C after Sonic Shear, mm^2/s	
NFPA Grade	Mnimum	Maxsimum
15	3.2	<4.0
22	4.0	<5.0
32	5.0	<6.3
46	6.3	<8.1
68	8.1	<10.5
100	10.5	<14.0
150	14.0	<18.2

During the development of the ASTM D 6080-97, studies [3] concluded that oil viscosity at pump inlet temperature after the 40 minute sonic shear test (ASTM D 5621) best correlated with the volumetric efficiency of a medium pressure vane pump. Combining this finding with the observation that mobile equipment operates at elevated temperature, led NFPA to define high temperature viscosity grades based on used oil viscosities after the 40 minute sonic shear test [4]. The minimum viscosity for a grade is based on the minimum viscosity of that ISO grade at 40 °C extrapolated to 100 °C using a VI of 100. The maximum viscosity for an NFPA grade is just less than the minimum viscosity of the next higher NFPA grade. In the NFPA classification, shown in Table 1, grades are continuous while they are discontinuous in the ISO 3448 viscosity classification.

1.2) Achieving High Equipment Efficiency

Extensive research [5, 6, 7] demonstrated that hydraulic system efficiency is dependent on the hydraulic fluid viscosity in actual service. The amount of fuel required to produce a given amount of work with a mobile hydraulic system can be significantly reduced by substituting a high viscosity index, shear stable hydraulic fluid for an OEM recommended straight grade hydraulic fluid. Energy savings of greater than 18% [8, 9], resulting from improved volumetric efficiency, were demonstrated in the field.

Under low temperature conditions, the efficiency of hydraulic equipment is dependent on the mechanical efficiency of the pumps and motors. High oil viscosity results in high frictional losses and, consequently, in low efficiency.

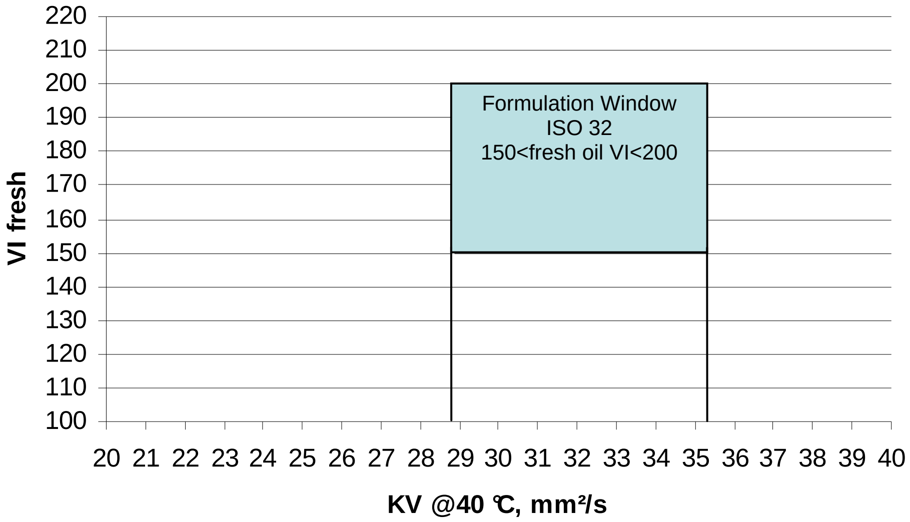
Therefore, in order to achieve high equipment efficiency under all operating conditions, a definition of Maximum Efficiency Hydraulic Fluids (MEHF) was proposed. For the most commonly used hydraulic oil grades (ISO 32, 46 and 68) it includes requirements for low and high temperature viscosity and a minimum Viscosity Index for the fresh oil. It also imposes a minimum viscosity at 100 ℃ after the sonic shear test. The rational and description of the MEHF guidelines were first introduced in March 2005 [7].

In 2008, the NFPA proposed an upgrade to its 2002 guidelines for hydraulic fluid selection [4]. The most important additions were a) the definition of the grades at 100 ℃ after the sonic shear test as shown in Table 1 and b) a requirement for a minimum VI of 160 after the sonic shear test. These additions were made to recognize the effect of sheared viscosity and VI on fuel economy and productivity of hydraulic equipment.

2. Options for selecting of hydraulic oils

Based on the previous review of the viscosity classifications and guidelines, hydraulic oil selection can be based on three sets of criteria, viscosity, VI and shear stability in the sonic shear test. Viscosity requirements can be defined at one or several temperatures, before or after shear. VI requirements can also be set for the fresh and/or the sheared oil.

Figure 1: Formulation window for the ISO 32 and fresh VI between 150 to 200



With so many possible combinations, identifying those that give the best possible way to select hydraulic oil that provides high equipment efficiency under a given range of temperature is a complex exercise. To address this issue, we decided to evaluate to which extent a set of viscosmetric criteria impacts the formulation window. A window corresponds to all the possible combinations of fresh oil viscosity at 40 ℃ for a given ISO grade and of fresh VI. Fig. 1 represents the window corresponding to the ISO 32 grade and oil having a fresh oil VI between 150 and 200.

Adding constraints reduces the size of the formulation window. If the window size becomes too big or too small, the constraints are too loose or too restrictive since they will include almost all or no commercial lubricants.

In order to obtain a graphical representation of the impact of the requirements included in the NFPA and MEHF guidelines on the formulation window, we prepared 216 formulations using Group I base stocks according to the design described in Table 2. Viscosity indices ranged between 150 and 200. The lower limit was selected because it corresponds to the minimum VI for fresh oils included in MEHF. The upper limit of 200 was selected because few commercial hydraulic oil formulations based on Group I base stocks exceed this value.

Table 2: Formulation Design

Parameter	Number of levels	Level description
ISO viscosity grade	3	32, 46, 68
Fresh oil viscosity at 40 ℃	3	Upper and lower limit and mid point of the ISO viscosity grade
Fresh oil Viscosity Index	6	150 to 200 by step 10
VI Improver	4	Shear Stability Index after the Sonic shear test ranging from 10 to 43

For each formulation we determined the three following characteristics:

- Viscosity at 100 C of the sheared oil after the sonic shear test (ASTM D 5621)
- Viscosity Index of the sheared oil after the sonic shear test
- The temperature at which the fresh oil reaches a viscosity of 750 mPa·s in the Brookfield viscometer according to ASTM D 2983.

These data were used to determine by linear regression analysis the equations that describe the dependence of the three characteristics mentioned above on the fresh oil viscosity at 40 ℃ and fresh oil VI. This analysis was completed for each of the four VI Improvers and each of the three ISO grades of interest. We obtained equations of the form:

Characteristic = a + b * KV@40 ℃ fresh + c * VI fresh

The precision of these 36 models was excellent with coefficients of determination (R^2) ranging from 0.9926 to 0.9999. The maximum and minimum errors between the actual and calculated characteristics are summarized in Table 3.

Table 3: Precision of the Models

	% Error on estimation of KV 100 ℃ after Sonic		Error on VI estimation		Error on T for 750 mPa·s estimation, ℃	
ISO	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
32	-0.8	1.1	-1	1	-0.1	0.1
46	-0.9	0.9	-1	1	-0.1	0.0
68	-0.9	1.0	-1	1	-0.1	0.1

3. Impact of the requirements on the formulation windows

We evaluated the impact on the formulation window of the requirements described in Table 4 for each of the four VI Improvers used in the study.

Table 4: Limits Imposed to the Formulation Window

Requirement	Unit	ISO grade	Limit	Origin
VI fresh		All	>150	MEHF
VI Sheared		All	>160	NFPA
KV 100 ℃ after Sonic shear	mm²/s	32	>5.9	MEHF
KV 100 ℃ after Sonic shear	mm²/s	32	>6.3	NFPA
KV 100 ℃ after Sonic shear	mm²/s	46	>7.5	MEHF
KV 100 ℃ after Sonic shear	mm²/s	46	>8.1	NFPA
KV 100 ℃ after Sonic shear	mm²/s	68	>10.0	MEHF
KV 100 ℃ after Sonic shear	mm²/s	68	>10.5	NFPA
Temperature for T=750 mPa·s	℃	32	<-15	D 6080
Temperature for T=750 mPa·s	℃	46	<-8	D 6080
Temperature for T=750 mPa·s	℃	68	<-2	D 6080

3.1 Formulation Window for VII 1 in the ISO grade 32

Using the equations describing the dependence of a characteristic of interest on the fresh oil viscosity at 40 ℃ and VI, we drew for each one the line that divides the formulation window into two areas where a given limit is met or not. Shown in Fig. 2.

The requirement for a viscosity at 100 ℃ after the sonic shear test of 5.9 mm²/s minimum, included in the MEHF guidelines for the grade 32, divides the formulation windows in two areas separated by the line AB. In the lower area, the formulations have a viscosity after shear lower than 5.9 mm²/s. In the upper area, the formulations have a viscosity after shear higher than 5.9 mm²/s.

In a similar manner, line CD that correspond to the minimum viscosity at 100 ℃ after the sonic shear test of 6.3 mm²/s for the NFPA grade 32, separates the formulation window into two areas. Increasing the after shear viscosity requirement from 5.9 to 6.3 mm²/s eliminates all the formulations in the ABDC area.

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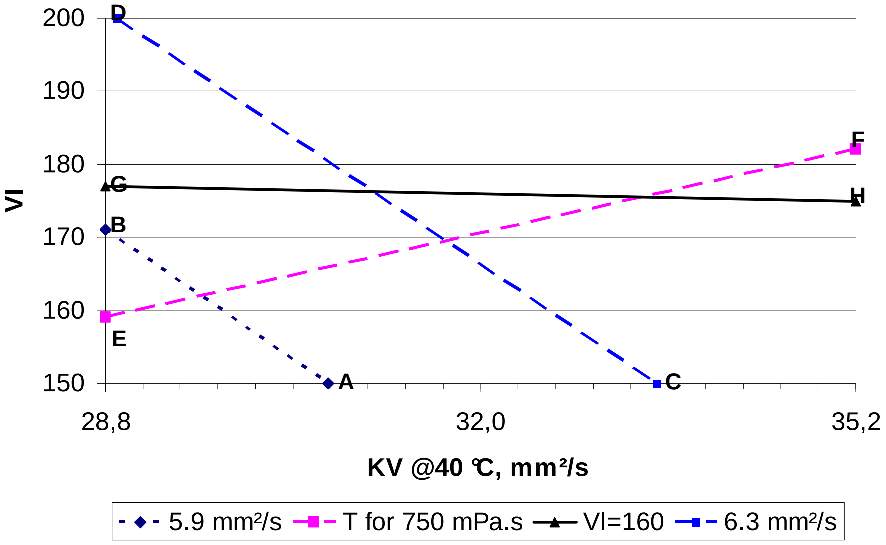

Figure 2: Formulation Window of the ISO VG 32 based on VII 1

In a similar manner, line CD that correspond to the minimum viscosity at 100 ℃ after the sonic shear test of 6.3 mm²/s for the NFPA grade 32, separates the formulation window into two areas. Increasing the after shear viscosity requirement from 5.9 to 6.3 mm²/s eliminates all the formulations in the ABDC area.

Line GH corresponds to formulations having a VI after sonic shear of 160 as required by NFPA. All formulations below this line have a lower VI after shear.

Finally, Line EF corresponds to formulations that have a Brookfield viscosity of 750 mPa·s at -15 ℃. Formulations below this line will have a viscosity higher than 750 mPa·s at -15 ℃ and will thus fall in the L32 grade according to ASTM D 6080. Those above the line will be L22 which is a requirement of MEHF for the 32 grade.

These four lines divide the formulation window into nine areas that correspond to different combinations of the four requirements as shown in Figure 3.

Only formulations in area 7 and 9 on Figure 3 meet both the MEHF and NFPA requirements. However, oils in area 9 are widely cross-graded L22-46 while oils in area 7 are L22-32 only.

The more widely cross-graded oils should provide the best overall equipment efficiency over a wide range of operating conditions. Oils in area 9 are L22-46, they have viscometric properties that give the best equipment efficiency and productivity within the domain of base oil, VI, viscosity and VI Improver that were investigated.

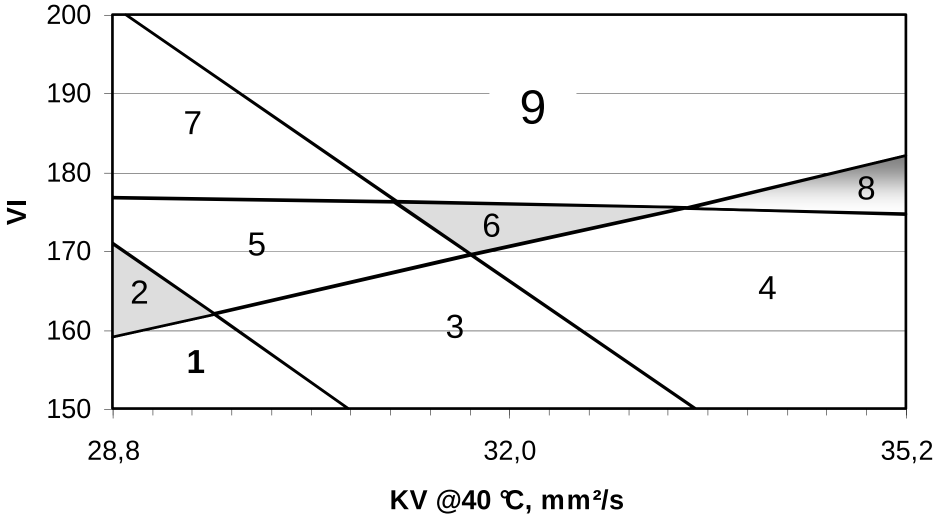

Figure 3: Areas Defined by the Four Viscosity Requirements – ISO VG 32 with VII 1

The viscosity requirements that are met by formulations falling in one of these nine areas are detailed in Table 5.

Table 5: Viscosity Requirements Met by the Nine Areas of the Formulation Window

Area	L Grade	NFPA Grade at 100 °C	Meet MEHF KV of 5.9 mm²/s at 100 °C	Meet MEHF L22 requirement	Meet NFPA VI >=160
1	32	32	No	No	No
2	22	32	No	Yes	No
3	32	32	Yes	No	No
4	32	46	Yes	No	No
5	22	32	Yes	Yes	No
6	22	46	Yes	Yes	No
7	22	32	Yes	Yes	Yes
8	32	46	Yes	No	Yes
9	22	46	Yes	Yes	Yes

3.2 Formulation Window for VIIs 2, 3 and 4 in the ISO viscosity grade 32

We plotted the lines corresponding to the four viscometric requirements for the three other VI Improvers used in this study. As shown in Fig. 4, moving from the more shear stable VII 1 to the less shear stable VII 2 has a dramatic effect on the size of the window that corresponds to the L22-46 grade. Using even less shear stable VI Improvers, further reduces the set of viscometric conditions that can be satisfied. This is shown in Fig. 5, 6. When using VII 3 or 4, it is not possible to reach a viscosity after shear at 100 °C of 6.3 mm²/s. Therefore, area 9 does not exist for these two VI Improvers within the scope of our study. It is still possible to formulate oils that meet the MEHF guidelines and fall in the NFPA L22-32 grade (area 7). The size of this area decreases with decreasing the shear stability of the VI Improver used.

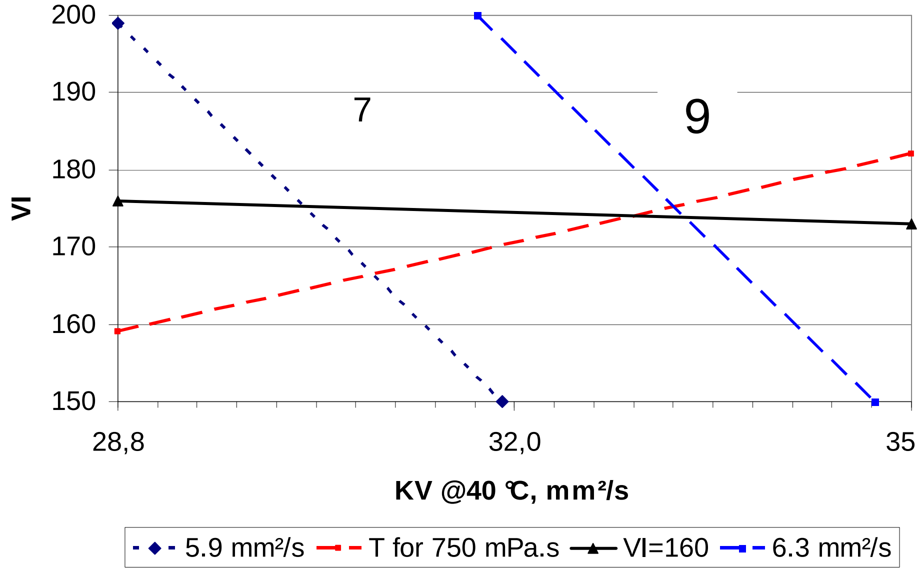

Figure 4: Areas Defined by the Four Viscosity Requirements – ISO VG 32 with VII 2

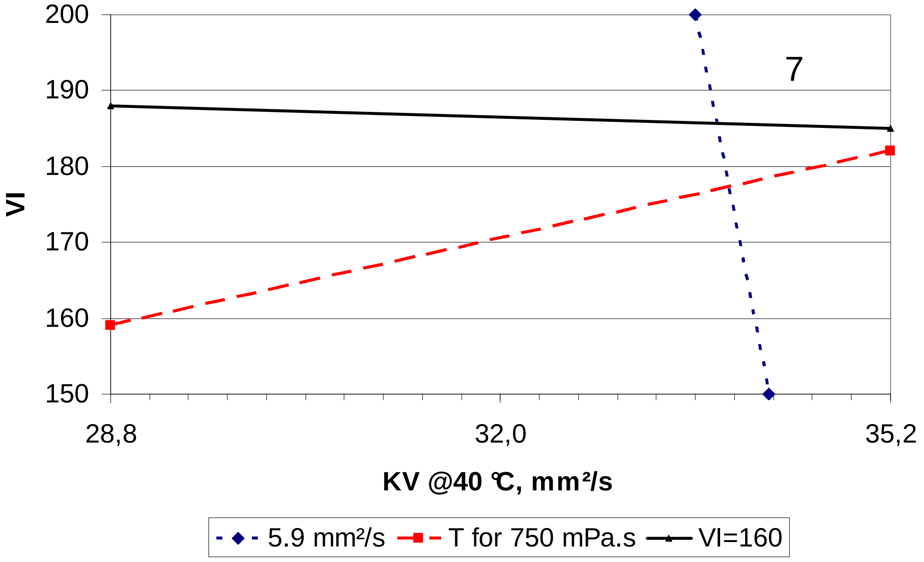

Figure 5: Areas Defined by the Four Viscosity Requirements – ISO VG 32 with VII 3

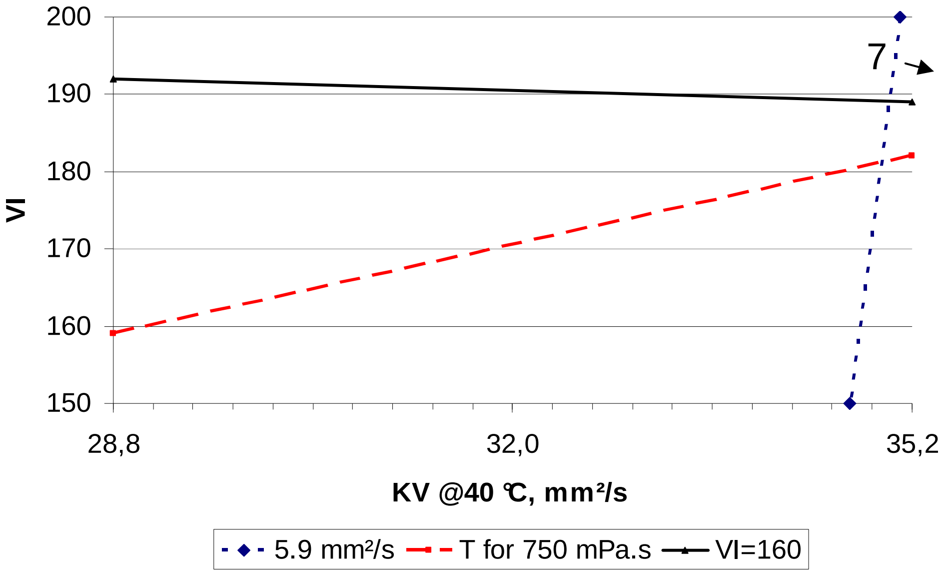

Figure 6: Areas Defined by the Four Viscosity Requirements – ISO VG 32 with VII 4

4. Formulating widely cross-graded oils with VI Improver 2

The previous results showed that it was possible to formulate widely cross-graded L22-46 oils using VI Improver 1 and 2. Data obtained on the ISO 46 and 68 formulations based on VII 2 were analyzed to determine the windows corresponding to the L32-68 and L46-100 formulations that meet both the NFPA and MEHF requirements. These formulation windows are labeled 9 in Figures 7and 8.

Comparing the formulation windows corresponding to area 9 for the three ISO viscosity grades based on VII 2 show that the size of this area increases when increasing the ISO viscosity grade. This may result from the fact that the higher the ISO viscosity grade, the higher the difference between the upper and lower viscosity limit at 40 ℃.

The size of the windows (area 7) for MEHF L32-46 and L46-68 with VI Improvers 3 and 4 also increases compared to that for the MEHF L22-32. However, these VI Improvers cannot be used to formulate MEHF and NFPA L32-68 or L46-100 since the viscosity of the oil at 100 ℃ after the sonic shear test is lower than the minimum specified by NFPA for the 68 and 100 grade respectively.

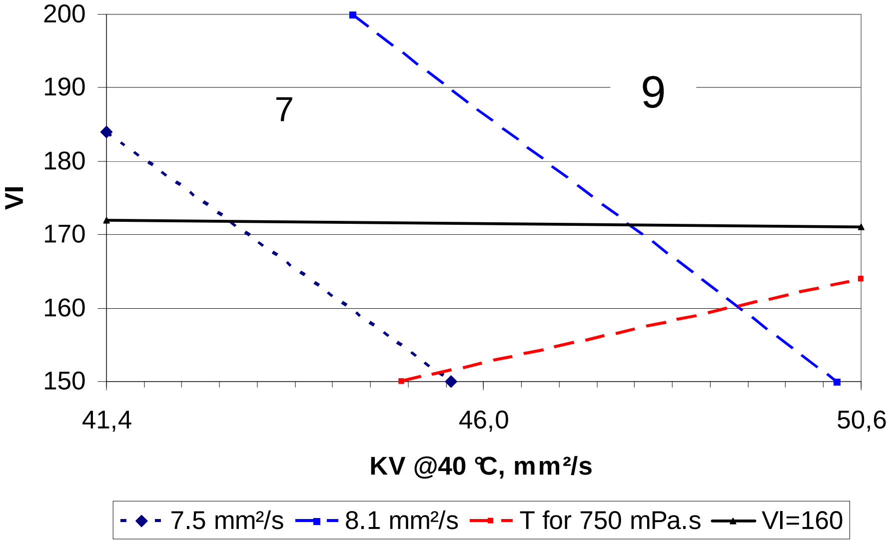

Figure 7: Areas Defined by the Four Viscosity Requirements – ISO VG 46 with VII 2

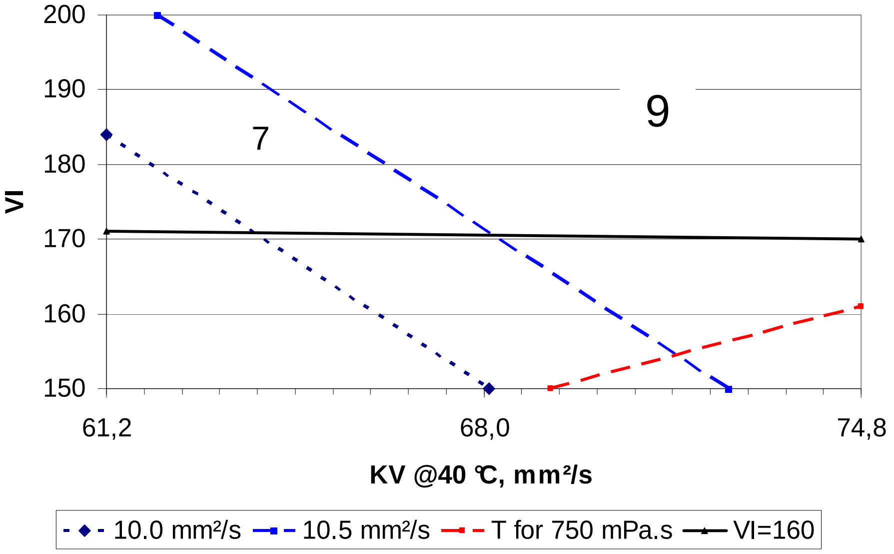

Figure 8: Areas Defined by the Four Viscosity Requirements – ISO VG 68 with VII 2

5. Impact of the VI Improver stability on the formulation window

Previous results showed that the windows corresponding to one of the four viscometric requirements considered in this study decreased with decreasing the shear stability of the polymer. We have represented in Figure 9, the formulation windows corresponding to the MEHF requirement of 7.5 mm^2/s minimum at 100 ℃ for the 46 grade. For each VI Improver, we drew the line that separates the window into an upper area where the viscosity at 100 ℃ after the sonic shear test is greater than 7.5 mm^2/s and a lower area where it is lower than 7.5 mm^2/s. VI Improvers 3 and 4 can hardly be used to produce ISO 46 oils with an after shear viscosity of 7.5 mm^2/s and cannot meet the requirement of the NFPA 46 grade which is 8.1 mm^2/s minimum after the sonic shear test.

The low temperature requirement of a maximum viscosity of 750 mPa.s at -8 ℃ for the L32 grade does not depend on shear stability since it is determined on the fresh oil formulation. Meeting the L32 requirement can thus be achieved equally easily by the four VI Improvers.

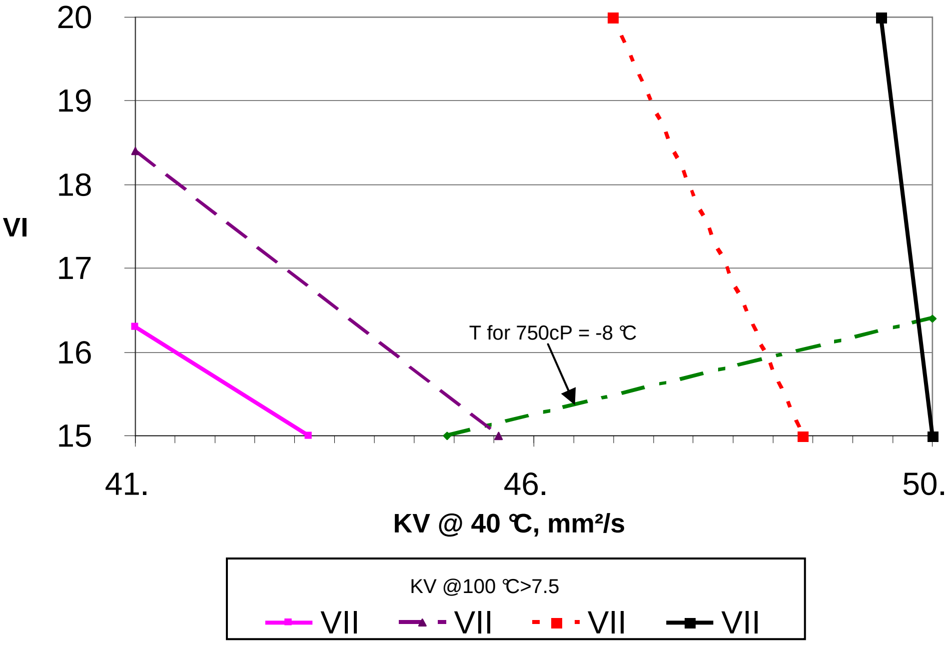

Figure 9: Formulation window for 7.5 mm^2/s for ISO VG 46 oils based on different VI Improvers

In a similar manner, we evaluated the effect of the NFPA requirement for a VI greater than 160 after the Sonic test. This was completed in the ISO 68 grade. Results are summarized in Figure 10.

The lines corresponding to a minimum of 160 VI after sonic shear are essentially horizontal lines. The higher the shear stability of the VI Improver, the lower the minimal initial viscosity index of the fresh oil. However, the differences between the VI Improvers are less important than for the viscosity after shear. The fresh oil VI has to be between 166 and 183 for the most and least shear stable VI Improver respectively to reach a VI of 160 after sonic shear as specified in the NFPA guideline.

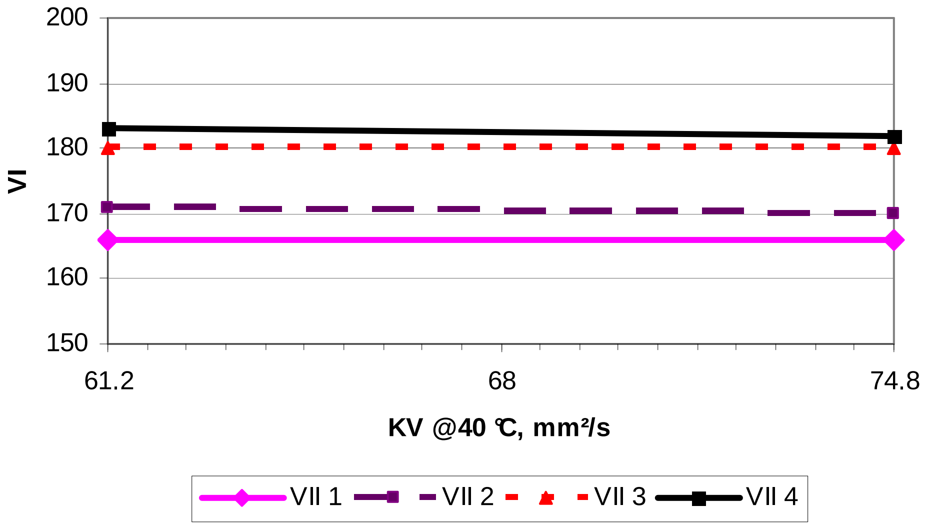

Figure 10: Formulation window for VI after sonic shear test greate than 160 for ISO 68 oils based on different VI Improvers

6. Conclusions

Extensive work conducted over thirty years by ISO, ASTM and NPFA amply demonstrates the need for providing all hydraulic industry stakeholders with a simple, meaningful and efficient way to classify oils. Other systems for defining oils with improved efficiency at both low and high temperature such as the Maximum Efficiency Hydraulic Fluid guidelines were recently proposed.

Comparing these guidelines to determine their ability to meet the objectives stated above was made possible by evaluating how they impact the size of the formulation window for three ISO viscosity grades (32, 46 and 68) based on four widely used VI Improvers with different shear stability levels. For this purpose, 216 blends were made with Group I base stocks and with a fresh VI ranging between 150 and 200.

Three critical characteristics were considered:

- The temperature at which an oil reached 750 mPa·s

- The viscosity of the oil at 100 ℃ after the sonic shear test
- The VI after the sonic shear test

For each value of these characteristics we can define a line that separates the formulation window into two areas in which the value is exceeded or not.

The limits for the three characteristics included in the NFPA and MEHF guidelines for an ISO 32 were:

- Temperature for 750 mPa·s = -15 ℃ (MEHF)
- Viscosity at 100 ℃ after sonic shear = 5.9 mm²/s (MEHF)
- Viscosity at 100 ℃ after sonic shear = 6.3 mm²/s (NFPA)
- VI after sonic shear test = 160 (NFPA)

Analysis of the results for formulations based on a shear stable VI Improver showed that the four lines divided the formulation window into 9 areas. Careful review showed that only one of them corresponds to highly cross-graded L22-46 formulations that meet both the requirements of the NFPA and MEHF guidelines.

Use of the less shear stable VI Improver 2 in the ISO 32 viscosity grade led to a reduction of the size of the high performance area discussed above. The two other less shear stable VI Improvers offer fewer formulating options and cannot be used to formulate widely-cross-graded fluids meeting the NFPA and MEFH guidelines.

Comparing the formulation windows for VI Improver 2 in the ISO viscosity grade 32, 46 and 68 showed that the higher the viscosity grade the larger the window corresponding to widely cross-graded formulations meeting the NFPA and MEHF guidelines.

It was noted that only a subset of the oils that met the NFPA and MEHF guidelines span three viscosity grades. This wide level of cross-grading is the most desirable for providing high efficiency benefits at both low and high temperatures.

Based on our findings, it appears that the optimum definition of a high performance hydraulic oil can thus be obtained by specifying for a given ISO viscosity grade:

- Fall in the next lower L grade as per ASTM D 6080.
- Fall in the next higher NFPA viscosity grade defined after the sonic shear test at 100 C.
- Have a VI after sonic shear higher than 160.

For example, in the case of an ISO VG 46 this corresponds to an L32-68, VI after sonic shear of 160.

Note

This paper has also been published at 2009 STLE Annual Meeting & Exhibition May 17-21, 2009, Disney's Coronado Springs Resort , Orlando, Florida, USA; and was also presented last January at the Esslingen Conference.

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UDK	ključne riječi	key words
621.892-822	hidraulički fluid maksimalne učinkovitosti MEHF	maximum efficiency hydraulic fluid MEHF
621.018.7	energetska učinkovitost	energy efficiency
621.83.032	hidraulički prijenosnici	hydraulic transmisions
532.13	viskoznost	viscosity
539.57	smična postojanost	shear stabilty

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