Low-Temperature Performance of Chinese Automotive Engine Oils – Status and Perspectives

Authors: Theodore Selby, Savant Group, Midland, Michigan, U.S.A.
Christian Neveu, Degussa, RohMax France S.A.S
Alex Tsay, Degussa China, RohMax Oil Additives, Shanghai, China

Abstract

Performance of automotive engine oils at low temperature has been extensively investigated in the last 50 years. The resulting understanding of engine oil rheology has been used to devise bench tests that predict their performance under cold starting conditions. Cold starting the engine has been essentially overcome for passenger car engines with fuel injection but pumpability of the engine oil has grown more demanding. Two tests (MRV TP1 and the Scanning Brookfield Technique with Gelation Index measurement) have become the measures of quality in pumpability response at low temperatures. As such they have become ASTM Methods and are included in a number of international specifications such as SAE J300 and ILSAC/API GF-1, 2, 3, and 4 accompanied by appropriate limits.

For a number of years, the Institute of Materials (IOM) has generated a database for Asia-Pacific engine oils for IOM Subscribers. This database can be used to assess and compare the performance of Chinese engine oils at low temperature to one another and to the larger world of engine oils also covered by the IOM database. This IOM survey of Asia-Pacific provides a complete 36-test analysis of 300 passenger car engine oils from the region including a wide range of chemical analysis, rheological measurements and performance assessments. In this paper we concentrate on the low temperature analysis of the rheology of samples collected in China since 2000.

The important factors affecting formulation of engine oils in China today are:

1. The recent inclusion of the MRV TP-1 and Scanning Brookfield Gelation Index requirements in China's National Standards for engine oil quality,
2. The availability of higher quality oils,
3. The higher treat rate of additives will require increased attention from the formulators in the selection of VI Improvers and Pour Point Depressants (PPDs).

In the latter case, new PPDs are likely to be required to provide formulators with robust and economical solutions to face these new challenges. Some examples will be given to illustrate the important effects of type and concentration of PPD on engine oil pumpability.

Introduction

From the beginning of the use of the passenger car, the low-temperature properties of engine oils have limited the use of these and heavy-duty vehicles in cold weather. Up to the 1960s and 70s the limitation was in starting the engine in cold weather [1]. After this problem was surmounted, another, more engine-damaging problem – to that time hidden by the startability problem – was revealed. This was the engine-threatening problem of low-temperature engine oil pumpability.

Startability Difficulties and Their Reduction

For many years starting the engine was the most critical factor in using the automobile because the starting motor and the first ignition of fuel in the engine had to overcome the high viscosity of the engine oil at low temperatures [1]. As mentioned, during the 1950s and 60s, development of fuel injection and electronic ignition plus the ability to make engine oils of lower viscosity at low temperatures overcame the startability problem. However, when low-temperature startability eased, another problem area was revealed that involved oil rheology – the latter was a problem that had been predicted earlier [2,3] from bench viscometry.

Pumpability

After the engine development made it much easier to start at low temperatures, it was found that with more engine use at low temperatures, wear in certain areas of the engine such as the valve train increased. Subsequent cold-room engine studies in the 1970s [4,5,6] indicated that such wear was associated with restriction or cessation of flow of engine oils at lower temperatures. Moreover, with continued study, it was found that this condition was not just caused by higher viscosities at lower temperatures but by the tendency of some formulated oils to form the gelation and air-binding of the oil pump previously predicted [2,3].

In particular, this gelated condition was a much more serious problem in comparison to lack of startability. That is, although not being able to start an engine is an inconvenience to the driver/owner, he or she still has a functioning vehicle to use another time. However, damage or destruction of the engine caused by lack of engine oil pumpability is catastrophic to the owner of the vehicle and completely removes it from use until repaired at considerable cost.

Investigations of Pumpability Failure

After confirmation of engine damage caused by lack of lubrication at low temperatures, studies of pumpability response began in the 1970s in North America [6]. Over the first period of study, it became clear that there was much to learn about the rheology of engine oil flow at low temperatures. The studies clearly showed two very different types of engine oil response to low temperatures – both flow-limited and air-binding behavior were demonstrated [4,5,6].

Flow-Limited Pumpability Failure

Flow-limited failure was expected as a consequence of higher viscosities at lower temperatures. However, it was considered a less serious form of pumpability problem because it could be anticipated and avoided with viscosity measurement. Moreover, higher viscosity made it more difficult to start the engine.

Air-Binding Pumpability Failure

It was found that, under certain cooling conditions, some engine oils could form the condition earlier called 'gelation' [3] – a rheological response of the oil in which a structural network encapsulated the more fluid portion of the engine oil. For some oils this would happen fairly repeatably under common cooling conditions in the cold room [5,6]. For other oils, gelation would not always occur but required carefully controlled combinations of cooling conditions – combinations that nature was adept at creating. Moreover, gelation could occur at surprisingly high temperatures – even at temperatures above 0℃ [7].

The process of air-binding the oil pump is shown in Figure 1. With a gelated network of oil and additives (#1 in Figure 1), under certain cooling conditions only the limited core of oil immediately above the oil-pump inlet in would flow into the pump under atmospheric pressure (#2). The gelated oil surrounding this hole had sufficient structure to prevent the oil from collapsing into this developing void and the hole would eventually reach from the oil surface to the oil screen. Air would then be pulled into the oil pump and from there pumped through, the supply lines (#3). It is evident that passage of air through the oil supply lines would quickly compromise lubrication and create conditions of considerable engine damage.

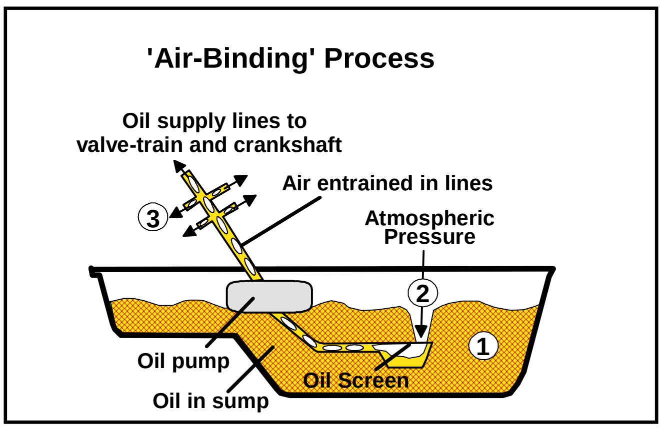

Figure 1 – Sketch showing the air-binding process.

Contributing Factors to Gelation

Regarding the components of the engine oil responsible for forming gelation, rheological studies in the 1950s [8], had shown that some basestocks would interact with engine oil additives – including certain forms of Viscosity Index Improvers (such as poly-isobutylene) to form gelated structures. In contrast, other VI Improvers would inhibit the formation of such structures and still others had no effect at all.

Pour Point Depressants

Polymeric and other additives that were strongly effective in preventing gelation (such as poly-methacrylates) were called Pour Point Depressants (PPDs), and, when used knowledgably, counteracted the gel-forming tendency of the formulated oil and prevented air-binding.

Testing and Predicting the Pumpability of Engine Oils

Finding these two forms of pumpability problems in engines quickly led to efforts to reproduce these on the laboratory bench and in cold-room engine tests [9].

The MiniRotary Viscometer (MRV) and ASTM Test Method D 3829

After evidence of engine pumpability problems was reported during the 1970s, a bench test instrument called the MiniRotary Viscometer (MRV) was developed with which the viscosity of oil could be measured by using a pulley and string system to turn a rotor in a stator. The oil was cooled to a chosen test temperature in 10 hours and soaked for another 6 hours. The MRV instrument and procedure showed good correlation with cold-room engine tests [10] and resulted in the generation of ASTM Test Method D 3829 in 1979 and publication in 1980 [11].

Engine Failures despite Use of D 3829

Unfortunately, in the winter of 1980 the Test Method D 3829 failed to predict the air-binding nature of a brand of oil leading to many engine failures in a northern area of the United States.

Very damaging air-binding occurred with this brand of oil under a set of subtle cooling conditions in which the temperature fell to -5℃, 'soaked' at that temperature for seven hours, and then dropped to -10℃ for another few hours. This combination of cooling conditions – which was considerably more subtle than simple cold-room tests – was proven to cause the epidemic of engine failures by the seminal work of Stambaugh and O'Mara in cold-room simulation of this field condition [12].

These authors also found that variation of <u>more than ±1℃</u> at the initial 'soak' temperature of -5℃ would not produce the air-binding condition that caused the engine failures. Moreover, if the temperature did not fall <u>at least 5℃</u> after the seven-hour soak, failure would also not occur. Their conclusion was that the primary gelation was formed at the -5℃ soak conditions and then augmented by at least a 5℃ decrease which would provide more structure and higher viscosity.

Their study, in reproducing one of obviously many potential cooling regimens of nature, made it obvious that cold-room engine tests were adequate only to predict gross air-binding performance of engine oil. As a consequence, the search for suitable bench tests began again.

The Scanning Brookfield Technique

Immediately following the epidemic of engine failures in 1980, efforts were made to obtain samples of the failing field engine oils since such samples would provide the basis for developing a suitable bench test. Such a bench test would have to correlate with the earlier ASTM cold-room failure data as well as with any field air-binding engine oil data.

The first instrument meeting these criteria was the Scanning Brookfield Technique (SBT) which was initially discussed [13] following Stambaugh and O'Mara's presentation. Using oil from the field failures, gelation was shown at the same temperature of -5℃ as in their engine cold-room work.

Figure 2 shows that when the SBT was also applied to the flow-limited and air-binding oils from the ASTM cold room studies, good correlation was obtained using the 5℃ difference of gelation-to-failure found by Stambaugh and O'Mara.

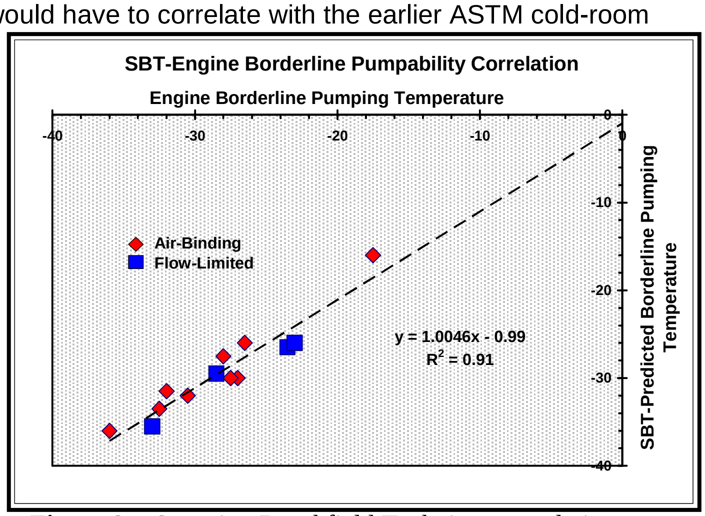

Figure 2 – Scanning Brookfield Technique correlation with engine cold-room borderline pumping temperature.

Normal Oils and Those Showing Gelation Index

The SBT is a simple rotational viscometric technique in which the oil is cooled at the slow rate of 1℃/hr while the viscosity of the oil is measured continuously at a very slow rate of spindle rotation (a shear rate of about 0.2 s^{-1}). The viscosity data thus collected is recorded and continuously computer-analyzed during the test for the oil's viscometric and rheological response. (For further information regarding the SBT's inception, development and application, the reader is directed to Reference [14]). The normal response of simple, non-gelating oil is an exponential change in viscosity with temperature. Any departure from this exponential relationship by a relatively sudden increase in the apparent viscosity of the oil is evidence of the formation of gelation. This is shown in Figure 3 with actual data obtained on two oils from the IOM collection of oils. One oil is normal and the other clearly shows gelation.

It will be noted that prior to the initiation of gelation, that latter oil shows a normal viscosity-temperature relationship without evidence of the gelation that occurs later.

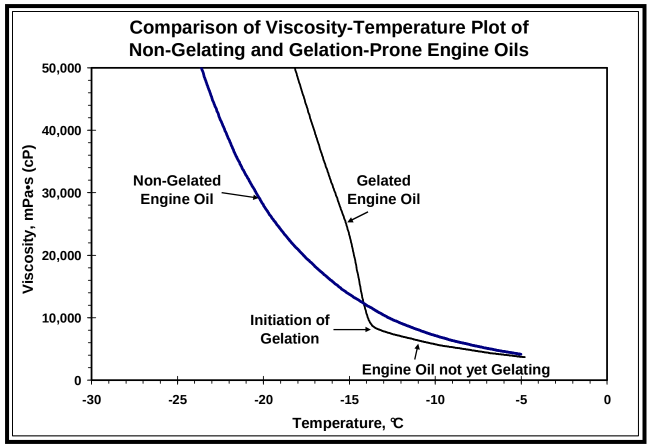

Figure 3 – Comparison of gelating and non-gelating oils

Gelation Index Determination

It was found informative to analyze the viscosity-temperature curves to determine the degree of departure from the normal viscosity-temperature relationship. Figure 4 shows this using the two oils of Figure 3.

Gelation Index is a measure of how much the viscosity of oil is departing from the expected exponential viscosity-temperature relationship as a consequence of the growing presence of gelation in the oil and its effect on the viscosity. The peak of the Gelation Index curve is called the Gelation Index value. For the gelating oil in Figure 3, Figure 4 shows that the value is 22.5 at -14.8℃. Both the Gelation Index and the Gelation Index Temperature are part of the ASTM Method D 5133 [15].

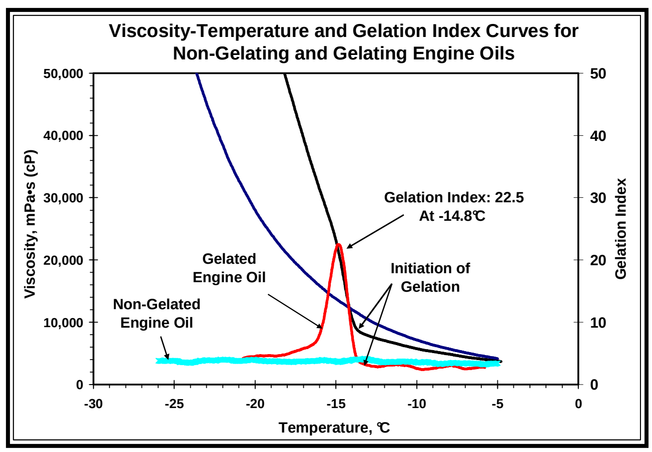

Figure 4 – Gelation Index curves co-plotted with viscosity-temperature curves of oils shown in Figure 2.

The critical Gelation Index used in automotive engine oil specifications is 12. It is based on a value of 16 which was shown in multiple analyses of the field-failing oil with the lowest value of Gelation Index. In practice, applying statistical analysis to assure that the determined value on the bench never exceeds the value of 16 (considering the precision of the method) the Gelation Index value is set in specifications at 12.

The MRV TP-1 Technique

Strong efforts were made to try to apply the MRV using different cooling cycles and the fruit of several studies culminated in a method called Test Profile 1 (TP-1) in 1985 [16] where it was given an ASTM number D4684 [17]. In comparison to the 16-hour cool-down of the earlier MRV technique, the TP-1 protocol calls for a quiescent exposure of the oil to 1/3℃/hour from -5℃ to -20℃. This latter termination of slow cooling was chosen on the basis of certain base oil studies from which it was assumed that no gelation of consequence would happen below this latter temperature. (While most heavy gelation occurs above -20℃, the IOM database indicates that failing Gelation Indices can occur as low as -40℃.) If a gelated structure develops in the oil, the mass needed to cause rotation of the rotor is called Yield Stress. The minimum load applied is 35 Pa and, if the rotor does not turn under this load, the oil is considered to have failed by Yield Stress – another term for gelation.

Comparison of the Two Methods

The SBT continuously stirs the sample slowly to induce any structure which will form under these low shear rate conditions. The technique generates viscosities and any gelation tendencies over the entire temperature range of analysis at 1℃/hr.

In contrast, the MRV TP-1 is a quiescent sample method and uses a slower cooling rate to -20℃ after which, as mentioned, it begins cooling at 2.5℃/hour to the temperature where a viscosity and/or Yield Stress value will be generated. As previously mentioned, rapid cooling ends the formation of a gel structure and TP-1 will only detect gelation when it occurs at -20℃ or above.

The Institute of Materials Engine Oil Database

The primary sources of complete information on engine oils in the world is the collection and analyses of engine oils obtained directly from the world's markets by the Institute of Materials (IOM). This well-used subscription service was started in 1984. Each year since then, it has collected hundreds of oils per year starting first in North America from 1984, then begun in Europe and Japan in 1992, and expanded to China and other Asian countries beginning in 1998.

Over 30 highly relevant tests are run on each engine oil. Many of these are required by engine oil specifications. Other tests are run to examine the important properties and performance characteristics of engine that seem most interesting to those who understand the use of these lubricants particularly in the areas of viscosity, rheology, oxidation, and composition.

To avoid questions of bias regarding the data, engine oils are purchased only from the market as would the automobile owner. This report covers oils collected from China, Europe and North America from 2000.

Comparison of IOM Engine Oil Pumpability Data

With such information available on the various properties of engine oils around the world, it was of interest to the authors to compare the quality of oils available on the markets in China to those available in North America and Europe with regard to pumpability data.

The Chinese engine oil market has grown rapidly over the last decade to keep pace with the even more rapidly growing automobile use by the Chinese population. All of these vehicles represent a large investment by their owners. Engine failure is can be an indication of inadequate engine oil formulation.

Strong efforts by the manufacturers of the engine oils sold in China – whether national or international – and equally strong efforts by governmental groups have focused on improving the availability of acceptable engine lubricants.

In view of the highly adverse effects of poor low-temperature pumpability – particularly the occurrence of air-binding – the authors have evaluated the IOM data base for engine oil pumpability response of oils marketed in China, Europe, and North America over the time period from 2000 to 2006.

Multi-Grade Engine Oils Collected from 2000 to 2006

In the period from 2000 to 2006, the Institute of Materials collected 285 multi-grade engine oils on the market in China, 689 multi-grade engine oils from Europe and 1531 of such oils in North America. Since all of these oils presumably would meet low-temperature pumpability requirements indicated by the SAE W-grade classification, it was of interest and concern to determine how many of these oils would actually pass TP-1 requirements as well as meet the pumpability performance criterion of the Gelation Index. In both cases, the greater concern was with gelation and consequent air-binding.

Pumpability of SAE Multi-Grade Engine Oils

China

Rapid growth of the automobile industry in China has generated a strong concern that these automobiles be served by engine oils and other lubricants equivalent to those required by engines and specifications in other parts of the world. This is a wise choice since the fine engines, made in China or elsewhere, require the same level of excellence. The very recent requirement in China National Standards of both TP-1 and Gelation Index measurement is a timely move in the direction of quality lubricants.

Overall Pumpability Response

Figure 5 shows results given by the engine oils collected from the market in China.

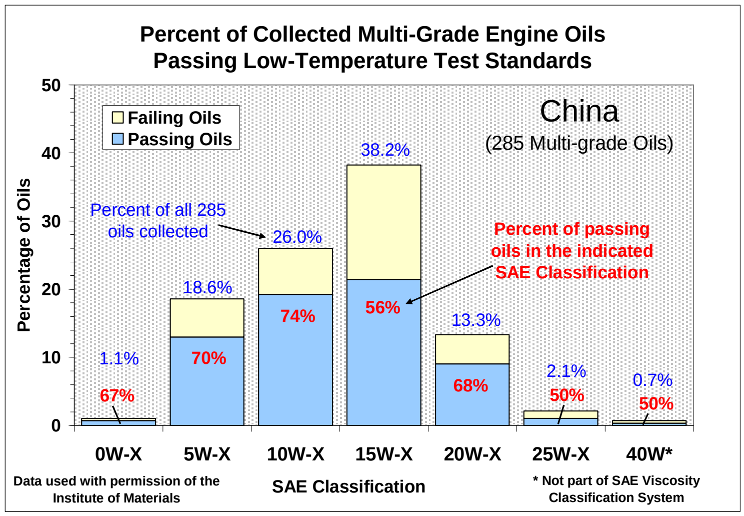

Figure 5 – Percentages of Chinese multi-grade oils collected and percentage passing for each multigrade designated.

The total height of the divided bars in Figure 5 show the percent of multi-grade engine oils falling into each of the six SAE Classifications, 0W, 5W, 10W, 15W, 20W, and 25W. (A seventh bar is for a unique 40W non-SAE designation.) The lower portion of each bar shows the percent of oils in that multi-grade category passing all three low-temperature pumpability bench tests.

It should be noted that, since IOM Collectors pick up oils as these oils are encountered during the collection periods, the different percentages shown by the overall bar heights are, to some degree, an indication of the distribution of oils available on the Chinese market. From this viewpoint, SAE 10W-X and 15W-X seem to be the two most popular multi-grade oils presented to the public in China followed by SAE 5W-X engine oils.

Pumpability Failure Modes

From the data of Figure 5, it is of interest to determine the pumpability failure modes of the oils in each SAE Classification. There are three modes of failure that are recognized:

1. A viscosity at the required low temperature of measurement of 60,000 mPa•s (cP) or more,
2. Presence of Yield Stress of 35 Pa at the required low temperature.
3. A Gelation Index above 12 over the temperature range from -5°to -40℃.

Figure 6 presents this analysis. The percent of oils failing each of the three modes of test in each of SAE multi-grade classification are plotted. The first three bars are failures by Yield Stress, Gelation Index, and flow-limited behavior, respectively.

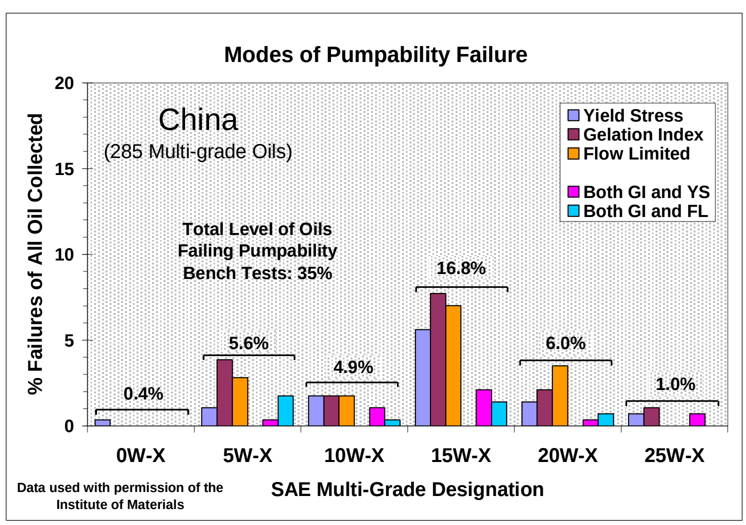

Figure 6– Analysis of modes of pumpability test failures for oils collected in China.

Yield Stress and Gelation Index are both measures of the tendency of oil to become air-binding in service.

In Figure 6, following the three bars for Yield Stress, Gelation Index and flow-limited modes, the last two bars are the percent of oils failing by a combination of two modes – either Gelation Index and Yield Stress or Gelation Index and Flow-Limited modes.

The percentages in Figure 6 shown above the brackets over the five individual and dual failure modes of each SAE W-X Classification is the total percentage of failing oils in that Classification of the total 285 W-X multi-grade oils collected and tested from China. Summing these percentage values shows the total percentage of engine oils collected in China that failed in low-temperature pumpability tests. At this time this latter value is 35% of the total multi-grade oils collected.

Fifteen percent of the failing oils failed by being flow-limited, 11% exhibited Yield Stress, and 18% had Gelation Indices over 12. (More than half the oils showing failing Gelation Index had values over 20.) Moreover, as shown, some oils failed by more than one mode. That is, 5% of the oils showed both Gelation Index and Yield Stress failure while 4% showed both Gelation Index and Flow-Limited modes of failure.

Europe

Overall Pumpability Response

Both gasoline and diesel European engines in the past have also failed by low-temperature pumpability problems of the air-binding type [6]. Thus, even though the southern portion of Europe is warm through most of the year, the northern portions – particularly including the Scandinavian and Russian areas – have weather that is both cold and variable in cooling rates. These areas can and have produced air-binding failures similar to those of North America [6].

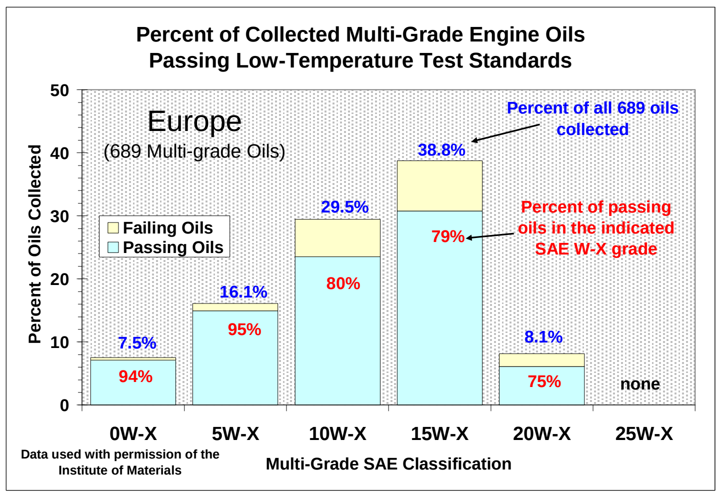

Figure 7 – Percentages of European multi-grade oils collected and percentage passing for each multigrade designated.

Figure 7 shows a view of European engine oils analyzed in a manner similar to Figure 5. As in China, the multigrade SAE Classification 15W – X seems frequently chosen. This is relatively closely followed by the SAE 10W-X Classification. Of these two most collected engine oils, about 80% pass the low-temperature pumpability tests whereas about 95% of the SAE 0W and 5W-X oils pass these tests.

Pumpability Failure Modes in Europe

Figure 8 gives a breakout of the three modes of low-temperature pumpability test failure in Europe similar to that of Figure 6 for China. Of the three modes of failure, failure by Gelation Index was the most frequently encountered, particularly for SAE 15W and 20W-X engine oils. Of the failing oils by Gelation Index values, over 50% exceeded a value of 20.

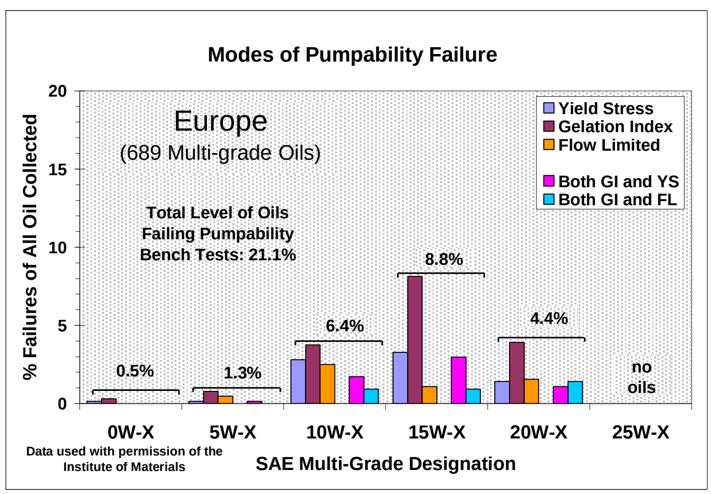

Figure 8– Analysis of modes of pumpability test failures for oils collected in Europe

Twenty-one percent of the oils collected failed to meet low-temperature pumpability standards. Of these failures about 6% were of the Flow-Limited mode, 8% had Yield Stress, and 17% had Gelation Index values above 12. Six percent of the oils failed to meet both Yield Stress and Gelation Index requirements and 3% failed both Flow-Limited and Gelation Index.

North America

Overall Pumpability Response

North American automotive engines are exposed to some of the world's most variable low-temperature weather patterns. These patterns cannot be anticipated by cold room testing and, even when known from the field, are difficult to reproduce in engine cold-room facilities. Such was the case in the previously mentioned 1980 epidemic of engine failures in the city of Sioux Falls, South Dakota, in the northwestern portion of the United States.

Figure 9 shows the overall low-temperature pumpability test response of 1531 engine oils from North America. The plot is similar to that of Figures 5 and 7 for Chinese and European engine oils, respectively. In North America, the more popular SAE multi-grade Classifications are, first, 10W-X with almost 50% of the oils collected falling into that category, and 5W-X covering almost 30% of the total multi-grade oils collected.

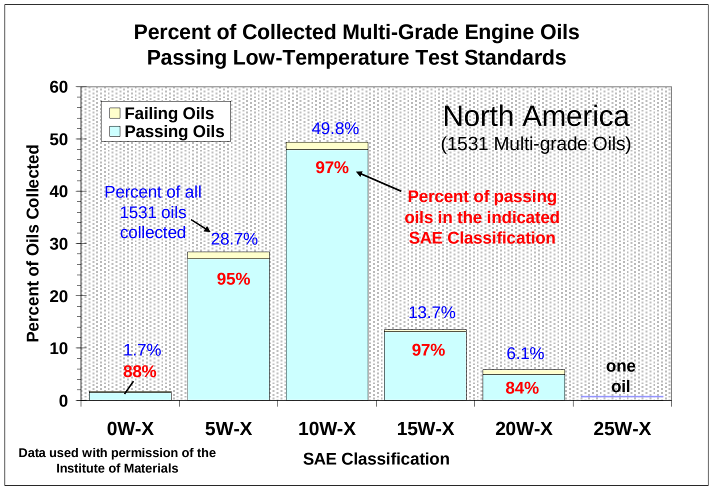

Figure 9 – Percentages of North American multi-grade oils collected and percentage passing for each multigrade designated.

Comparison of Figure 9 to Figures 5 and 7 show considerably higher percentages of North American oils meeting low-temperature pumpability standards.

Pumpability Failure Modes in North America

Figure 10 shows the failure modes among the six SAE multi-grade classifications. Figure 10 is similar to Figures 6 and 8 except that the ordinate (Y-axis) is limited to 5% instead of 20% in order to view the low levels of pumpability failures.

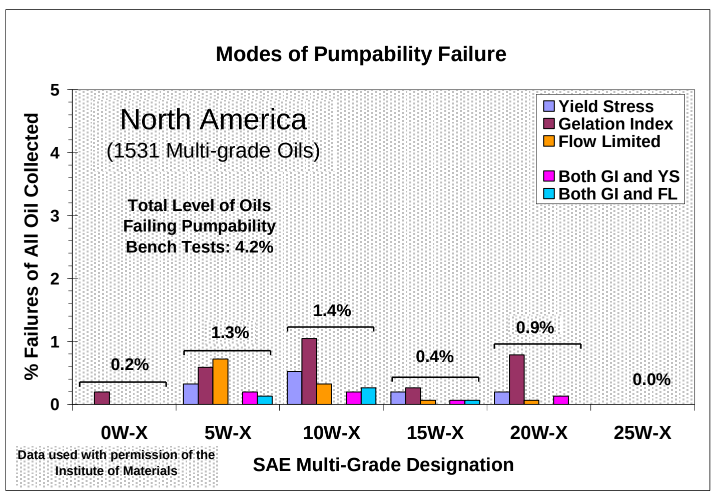

Figure 10 – Analysis of modes of pumpability test failures for oils collected in North America.

The total level of pumpability failure for the 1531 engine oils collected is 4.2%. Of these oils failing pumpability tests, a little over 1% failed by Flow Limited mode, over 1% by Yield Stress, and over 3% by Gelation Index. Regarding dual failure modes, 0.6% failed both Gelation Index and Yield Stress, and 0.5% failed by Gelation Index and Flow-Limited modes.

Discussion

Significance of Pumpability Data Presented

General Observations

One way of considering the data of Figures 5 through 10 is from the viewpoint of the experience and tolerance to the low-temperature pumpability of their respective engines oils in different areas of the world.

Basis of North American Pumpability Control

The occasional dramatic and costly experience, such as the North American Sioux Falls incident, plays a strong role in forming subsequent specifications. This is very evident in the differences among the low-temperature pumpability failure levels in China, Europe, and North America. It is quite clear from the IOM data that North America rigorously controls the low-temperature properties of its engine oils in comparison to Europe and China.

Progressive Engine Damage

However, the occasional dramatic experience only makes the effects of poor engine oil pumpability quickly apparent. Private studies in the 1990s (one of which was conducted by one of the authors) have shown that in North America, the frequency of engine camshaft problems for an arbitrarily selected brand of engine increased significantly when dealerships were canvassed while traversing the North American continent northward from southern states of the United States to northern Canadian provinces.

These forms of problems caused by low-temperature pumpability can be easily interpreted as poor engine maintenance by the owner, or harsh driving conditions, etc., when, in fact, they are a direct influence of poor engine oil pumpability. Moreover, the damage that occurs is additive rather than sudden (as in the Sioux Falls type incidents). It is thus very difficult to clearly attribute such damage to the lubricant unless it is measured for conformity to low-temperature pumpability standards.

Essentially, controlling low-temperature pumpability eliminates one unnecessary cause of engine damage and provides greater understanding of other factors that may be involved in engine malfunction.

Knowledge and Attitudes toward Pumpability Control

The data presented in this study suggests that control of low-temperature engine oil properties regarding pumpability may reflect several factors among which are:

1. Varying levels of knowledge in how to obtain the desired performance of the formulated engine oil.
2. Varying levels of perceived importance of low-temperature pumpability,
3. Variation in base stock properties of ostensibly the same identification.

Engine Oil Formulation Experience

Both Europe and North America have many years of experience in the formulation of engine oils. China, with all of its inherent abilities, is a relative new-comer, particularly in familiarity with additive technology and interaction of these additives and the base oils available. On the other hand, with the growth in developing and applying China National Standards, China is rapidly raising the technical levels of excellence that are important to engine protection. It is expected that the relatively poor low-temperature pumpability quality levels shown by the IOM database up until 2006 will now change significantly for the better.

The Factor of Perceived Importance

Despite Europe's long experience in engine oil formulation, the level of low-temperature pumpability failure of their multi-grade engine oils is more similar to that of China. Neither the first or third factors above would seem to apply. This leaves only the second factor to be considered.

Furthermore, the low-temperature pumpability limits of the ILSAC specifications regarding Gelation Index are not generally applied in Europe. It would seem that the combination of insufficient motivation perhaps caused by lack of perceived importance might account for the results shown in Figures 7 and 8.

The widely variable climate of Europe is likely an influence on the European level of control of low-temperature pumpability. On the other hand, as in North America, it is not uncommon for a motorist to drive from relatively temperate climes into colder regions of Europe where air-binding conditions were encountered in the past as mentioned earlier in the paper.

Base Stock Considerations

In all three of the world areas discussed in this paper there is a transition in the quality of basestock. Group 2 basestocks are becoming more prevalent since they can be recovered from all quality levels of crude oil and have several excellent properties including high Viscosity Indices and good oxidation resistance.

However, these basestocks also have inherently poorer low-temperature pumpability tendencies because they are also highly paraffinic in nature. As a consequence, they have a natural tendency to form wax crystals and to gelate giving rise to air-binding. It is thus very important with such basestocks to be assured that the resulting formulated oil is acceptable by the proper use of pour-point depressants (PPDs). Moreover, remembering the experiences created in the past by nature, each batch of engine oil should pass all low-temperature pumpability standards.

Conclusions

The evaluation of the Institute of Materials Engine Oil Databases for China, Europe, and North America has shown that both differences and similarities exist among them regarding the important property of low-temperature engine oil pumpability for SAE Classifications of multi-grade engine oils.

Of the three world areas, North America showed greatest control of pumpability with a weighted average passing level of 96% of the IOM collected oils. Europe had a weight average passing level of performance of 83% and China showed a level of performance of 65% passing oils.

Factors which were likely responsible for these differences between regions of the world have been discussed. For China the application of Gelation Index and TP-1 will change the quality level of engine oils marketed in China considerably.

Europe, with its long experience in formulation, the factor of perceived importance was more likely associated with its comparatively low level of performance. That is, low-temperature pumpability problems are perceived as not being of great importance in the dominant areas of Europe even though Scandinavian countries have reported problems in the past. Europe would benefit considerably in the low-temperature pumpability quality of its oils if various governments followed the example of China in requiring compliance with standards such as Gelation Index and TP-1.

Lastly, it has been noted that while the increasing use of Group 2 basestocks brought improved viscosity-temperature behavior and higher resistance to oxidation, Group 2 basestocks also brought greater susceptibility to gelation and the associated occurrence of air-binding unless the engine oils to be made from them were carefully formulated and tested.

Bibliography

[1] Selby, T.W., **"A Comparison of the Effects of Cranking Speed and Oil Viscosity on Low-Temperature Engine Starting,"** *SAE Progress in Technology, Volume 10*, pp. 11-14, 1966. Originally presented in SAE Paper 805C, Jan. 13-17, 1964.

[2] Moyer, R.G., **"Low-Temperature Pumpability of Oils,"** *Lubrication Engineering, Vol. 18*, No. 4. p. 165-168, 1962.

[3] Selby, T.W., **"Viscosity and the Cranking Resistance of Engines at Low Temperatures,"** *Proceedings of the Sixth World Petroleum Congress, Frankfort am Main, Section VI, Paper 17,* pp. 1-16, June 19th-26th, 1963.

[4] McMillan, M.L.: Stewart, R.M.: Smith, Jr., M.F., and Rein, S.W., **"Low-Temperature Engine Oil Pumpability in Full-Scale Engines,"** SAE Paper 750691, 1975.

[5] **Low-Temperature Pumpability Characteristics of Engine Oils in Full-Scale Engines,** *ASTM Data Series Publication 57,* pp. 1-99, 1975.

[6] Shaub, H., **"A History of ASTM Accomplishments in Low Temperature Engine Oil Rheology: 1966-1991,"** *ASTM STP 1143, Low Temperature Lubricant Rheology Measurement and Relevance to Engine Operation, Ed. R.B. Rhodes,* pp. 1-19, 1992.

[7] Selby, T.W. and McGeehan, J.A., **"Low Temperature Rheology of Soot-Laden, Heavy-Duty Engine Oils Using the Scanning Brookfield Technique,"** *SAE Paper #2006-01-3352, SAE World Congress, Detroit, Michigan,* April 3-6, pp. 1-12, 2006.

[8] Selby, T.W., **"The Non-Newtonian Characteristics of Lubricating Oils,"** *ASLE Transactions, Vol. 1, No. 1,* pp. 68-81, 1958. Originally presented at Annual Meeting of ASLE, Detroit, Michigan, April, 1957.

[9] SAE Subcommittee 2 appoints Task Group to study field reports of pumpability problems. On the basis of the information's requests ASTM to develop a simple bench test to measure pumpability of engine oil. See [4], p. 5; actions taking place through 1970-71.

[10] Shaub, H., Smith, Jr., M.F., and Murphy, C.K., **"Predicting Low-Temperature Engine Oil Pumpability with the Mini-Rotary Viscometer,"** *SAE Paper 790732, Published in SAE-460 (ASTM STP-621-S4),* pp. 107-124, 1979.

[11] ASTM Method D 3829, **"Standard Method for Predicting the Pumpability of Engine Oils,"** *published in ASTM Handbook of Methods,* 1979.

[12] Stambaugh, R.L., and O'Mara, J.H., **"Low-Temperature Flow Properties of Engine Oils,"** *SAE Paper 820509,* 1982.

[13] Selby, T.W., Written and oral discussion of **[12]** presenting Scanning Brookfield Technique data on field-failing oil, 1982.

[14] Selby, T.W., **"The Scanning Brookfield Technique of Low-Temperature, Low-Shear Rheology – It's Inception, Development, and Applications,"** *Ibid. ASTM STP 1143,* pp. 33-64, 1992.

[15] ASTM Method D 5133, **"Standard Method for Low Temperature, Low Shear Rate, Viscosity/Temperature Dependence of Lubricating Oils Using a Temperature-Scanning Technique,"** *published in ASTM Handbook of Methods,* 1990.

[16] Henderson, K.O.; Manning, R.E.; May, C.J.; and Rhodes, R.B., "**New Mini-Rotary Viscometer Temperature Profiles That Predict Engine Oil Pumpability,"** *SAE Paper 850443,* 1985.

[17] ASTM Method D 4684, **"Standard Method for Determination of Yield Stress and Apparent Viscosity of Engine Oils at Low Temperature,"** *published in ASTM Handbook of Methods,* 1987.