

Studies of the Flow and Gelation Response of Jet Fuels at Critical Low Temperatures

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Abstract

Many jet aircraft fly at altitudes and ambient temperatures exposing the jet fuel to temperatures well below -40°C . Operation of aircraft at low ambient temperatures and at higher altitudes is highly dependent on the low-temperature flow properties of the jet fuel used. However, these fuels vary widely in manufacture around the world and in quality levels within a given hierarchy of fuels from commercial Jet A and Jet A-1 to military JP-4 through JP-8 and more extended fuels.

Thus, the low-temperature viscosity and rheology of jet fuels is a primary consideration in determining the temperature range within which the aircraft can be operated. In particular, the tendency of the fuel to form a congealed or gelled condition at temperatures below -40°C can markedly restrict the operation of the aircraft both in altitude and in flight path.

This paper shows application of the Scanning Brookfield Technique to determine the viscosity and gelation tendencies of jet fuels over a range of temperatures down to -65°C . Of critical significance, the paper presents information on the practicality of additive treatment approaches to significantly improve the operational range of jet fuels at these very low temperatures.

Introduction

Low-Temperature Flow of Jet Fuel

Four of the limitations in the use of jet aircraft are closely intertwined. These limitations are operational speed, altitude, range, and fuel efficiency. Interestingly, all four are directly or indirectly affected by the behavior of the chosen jet fuel at low temperatures.

Jet aircraft flying at the higher altitudes desired for fuel efficiency, range, and speed are limited by the temperatures at which the fuel will form crystals or otherwise thicken – a condition defined in this paper as ‘gelation’ – (the terms ‘gelation’, ‘crystallization’, and ‘congealing’ will be used interchangeably in this paper). This rheological property of fuels is more critical in military aircraft which must operate in extreme temperature environments at high efficiency and at long ranges. Great circle polar flights of both military and commercial aircraft combine low-ambient and high altitude effects since even flying at lower altitudes which may hold equally cold air conditions may not necessarily end or reduce the problem of gelation.

It is obviously critical to have a means of testing jet fuel for vulnerability to gelation conditions – preferably a technique dependable and accurate. More than this, the technique should be applicable in ongoing efforts to find ways to improve the low-temperature behavior of fuels normally poorer in low-temperature performance.

Older techniques developed in the 1920s to determine low-temperature pourability of oils and hydraulic fluids have been found unsuitable but no better technique has been available. However, a relatively recently developed technique has shown the ability to not only determine the viscometric response of jet fuels over the entire critical temperature range of interest but to also predict the onset and severity of gelation tendencies.

This paper presents some new work using the Scanning Brookfield Technique, a method and instrument developed in 1980 to resolve the cause of low-temperature pumping failure of engine oils and since used for a number of studies (summarized in Reference [1]). It is now an ASTM test method – D 5133

[2] and has been made part of several specifications and other applications requiring full knowledge of the flow behavior and tendency to form gelation structures and macroscopic molecular associations in the fluid.

The Scanning Brookfield Technique (SBT) and Instrument

Instrument – Figure 1 shows one of the SBT instrument made by the Tannas Co. The model shown is the PlusTwo – smallest of the Tannas models made (largest is the PlusEight capable of handling and automatically recording data from eight viscometer heads). For the PlusTwo, two special viscometer heads (made exclusively for Tannas by Brookfield Engineering) are connected to two matched rotor-stator cells (shown more clearly in Figure 2). Under each viscometer head is an adapter which rigidly and coaxially couples the rotor and stator cell to the viscometer head.



Figure 1 - Tannas PlusTwo bath and viscometer heads with computer and programs

A programmable temperature controller on the bath controls the ramping rate and temperature range desired. Bath temperature and the torque required to turn the rotor in the stator are continuously recorded by the computer shown to the right of the bath in Figure 1.

The Tannas PlusTwo bath has a cascade cooling system and is capable of imposing temperatures from +30° to -75°C and can linearly ramp the temperature of the test fluid down (or up) at essentially any rate at which the bath can respond.

Computer programs automatically

1. calibrate the viscometers,
2. receive and record the bath temperature and viscometer torque data,
3. use the calibration data to calculate the viscosities of the fluid tested at the temperature recorded, and
4. use the viscosity and temperature data to measure the rate of change, compare this to the expected exponential rate of change and from this to measure the presence and effect of gelation. The resulting curve is called the Gelation Index curve and the highest value of the peak(s) generated is the Gelation Index.

Method of Test – Since most fluids that have a tendency to form gelation at a lower temperature will retain some degree of ‘memory’ of that condition when brought to ambient temperature. Thus, it is necessary for the test fluid’s thermal history to be erased by exposure to some acceptably higher temperature for a selected time (e.g. for engine oils ~95°C for one hour).

The range of temperature of interest and the ramping rate are entered into a programmable temperature

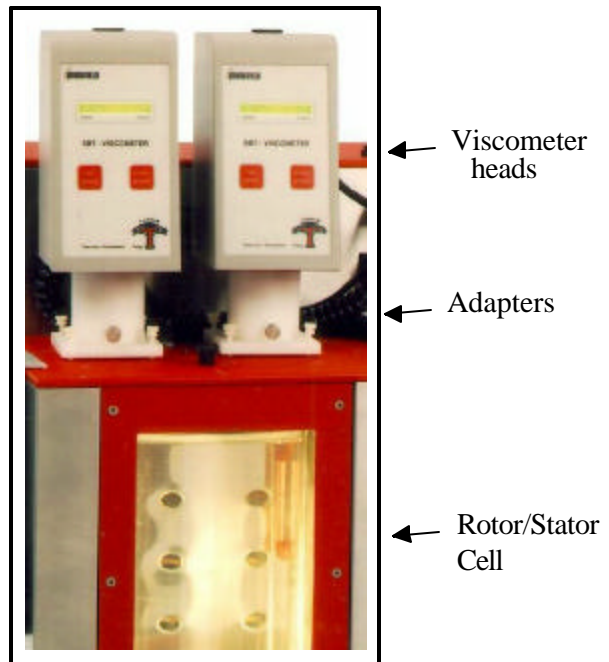


Figure 2 - Close up of viscometers, adapters and cell in bath

controller or into a computer program. When preparing for analysis, the test fluid is poured into the stator and brought to the temperature needed for erasing any thermal history. After a suitable time, the rotor is placed in the stator thus completing the viscometer cell. A sleeve is placed around the stator and the sleeve inserted into the alignment fixture coupling the cell to the viscometer head as shown in Figure 2.

The entire assemblage is set on the viscometer bath with the stator and rotor immersed in the low-temperature bath (see Figure 2) which has previously been brought to the initial temperature. The viscometer head is then turned on to the desired rotor speed and the bath ramping rate initiated. Several viscometer heads can be run simultaneously and, as mentioned earlier, a computer program receives both viscometer torque and bath temperature to automatically record the viscosity-temperature curve.

Gelation Index – Although the SBT has been used on engine oils since 1980, recognition of the need for a method of determining the temperature and magnitude of gelation led to the development of the Gelation Index in 1991 by Selby [3,4]. A program was generated for the purpose and it was found that the resulting Gelation Index curve was highly repeatable both in the magnitude of gelation measured and the temperature at which it occurred [3].

Past Recognition of the Problem – The commonly used commercial jet fuel is Jet A. In great-circle routes over polar regions, Jet A-1 fuels are more low-temperature tolerant. Table 1 shows the low-temperature requirements for these and other jet fuels in use.

Depending on the jet fuel used, for commercial planes on long flights at the relatively high altitudes needed to increase speed and efficiency, the FAA requires airlines to deviate course to warmer regions when fuel temperature in any one of the wing fuel tanks comes within 3°C of the so-called Specification Freezing Point for the fuel (not to be confused with the ASTM Freezing Point of Aviation Fuels, ASTM D2386 [4]).

Essentially, this FAA Specification Freezing Point is 3° to 5°C higher than the cloud point of the fuel (ASTM Test Method D 97 [5])

at which temperature the fuel will flow readily. Thus this Specification Freezing Point is a ‘fail-safe’ approach in the absence of a more direct measure of the rheology of these fuels and places a considerable penalty on fuel use. When the aircraft is following great circle routes, diversion from the flight plan significantly increases the distance to the destination as well as the estimated time of arrival and, obviously, the cost of operation. Flights likely to encounter colder temperatures such as great-circle flights to Europe from North America may use

For military aircraft, the choices are considerably more demanding and difficult, particularly in polar operation. Long-duration, high altitude aircraft flights have recorded free air temperatures as low as -90°C. While specially refined fuels are available with very low freeze points they cost significantly more than Jet A or Jet A-1 (the refinery cut used for JP-8) and require special handling and segregation. For these reasons, selection of fuels for low-temperature performance by the military is more critical. The special refining techniques severely limit its availability and increases the difficulties of logistical support of military bases scattered around the world. Much interest has been generated in finding ways of improving the more readily available jet fuels, particularly Jet A-1, for both military and commercial usage.

Table 1 - Low-Temperature Requirements For Jet Fuels			
Description	Abbr.	Freeze point max	viscosity max
standard commercial jet fuel	JET A	-40°C	8 cSt at -20°C
Civilian aviation fuel for low temperature climates, (standard fuel in Europe)	JET A1	-47°C	8 cSt at -20°C
General US military turbine fuel	JP-8	-47°C	8 cSt at -20°C
Standard Navy turbine fuel	JP-5	-46°C	8.5 cSt at -20°C
Jet propellant thermally stable, narrow cut for military use	JPTS	-53°C	12 cSt at -40° C
Replaced by JP-8	JP-4		

Initial Experimental Studies

First Application of the Scanning Brookfield Technique to Jet Fuels

Since the SBT could be applied to problem areas other than engine oil, Selby and Müller ran a series of tests on other fluids including jet fuel [6]. These first studies of three jet fuels gave considerable evidence of gelation as shown in Figures 3, 4, and 5.

All three of the jet fuels tested showed sharp gelation peaks and high Gelation Indices (all were greater than 70) with obviously high contributions of the gelation to the measured viscosities as shown by the viscosities before and just after the break point. However, it is very significant that the viscosity-temperature curves just prior to the viscosity and gelation breaks were the normal exponential relationship associated with simple flow of fuels in the absence of gelation.

Figure 3 shows results on a Jet A commercial fuel made by one manufacturer. The data show that very strong gelation occurs relatively sharply at -46°C . The rapidly rising viscosity indicates the effect of the gelation. At about 25 cP the viscosity increase becomes slightly more gradual indicating that the gel-forming components have (at this temperature) become exhausted but are still present and contributing to the viscosity. It is interesting to note that the Specification Freezing Point minimum temperature (below which a commercial aircraft would have to divert its flight path) is -37°C . The actual temperature of concern is -46°C which means that the onset of gelation is 9°C below the “fail-safe” FAA value.

Figure 4 shows results on a Jet A-1 fuel whose Specification Freezing Point is -44°C . The Gelation Index Curve breaks so sharply at -51.8°C that it may reflect massive crystallization in the fuel. However, there is a 10°C difference between the Specification Freezing Temperature and the actual gelation/crystallization temperature. This difference can make considerable difference in necessary extension of the flight paths required for commercial airlines in great circle flights.

Figure 5 is another similar Jet A-1 fuel with a somewhat higher viscosity-temperature curve than in Figure 4 before the viscosity/gelation break point at -51°C .

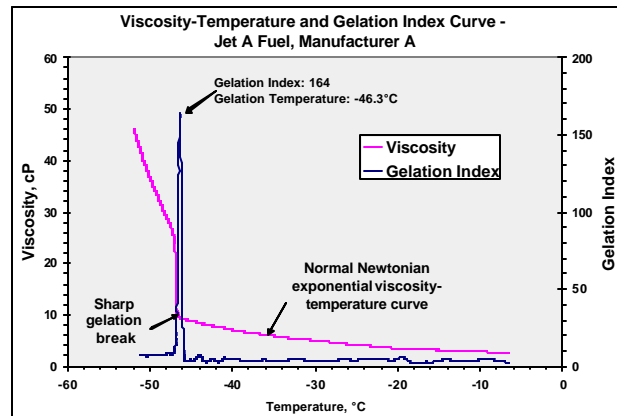


Figure 3 - Viscosity-temperature and Gelation Index of Jet A fuel, Manufacturer A

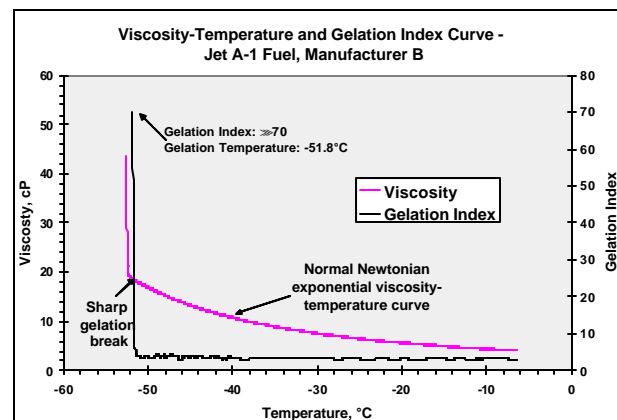


Figure 4 - Viscosity-temperature and Gelation Index of Jet A-1 fuel, Manufacturer B

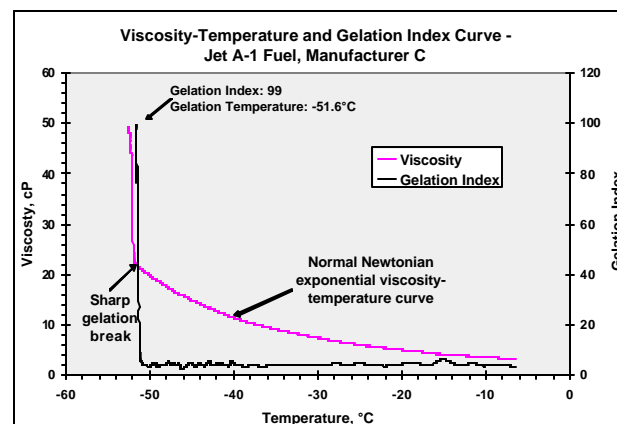


Figure 5 - Viscosity-temperature and Gelation Index of Jet A-1 fuel, Manufacturer C

The Molecular Physics of Jet Fuel at Low Temperatures

General Considerations Regarding Gelation - The original development of the Scanning Brookfield Technique was based on a conception of the behavior of a heterogeneous mixture of mineral oil hydrocarbons [7]. At sufficiently high temperature, the individual groups of homogeneous molecules were thought of as forming a miscible group of liquids. As temperature decreased, those molecules that would in the pure state normally form a solid instead are soluble in those hydrocarbons remaining liquid. As temperatures continue to decrease, more and more of the molecules forming each distinct hydrocarbon pass from the liquid state to the soluble state – some perhaps through the intermediate state of liquid crystals. At some point, the remaining, normally liquid, hydrocarbons are no longer capable of holding the once-soluble hydrocarbons in solution. These latter molecules begin to precipitate in crystalline particles which may (or may not) form latticework structures which increase the viscosity of the fluid. The continuous slow rotation of the rotor in the Scanning Brookfield Technique was originally chosen to encourage such structural formation by bringing the molecules in the precipitation state into proximity. In the presence of the higher viscosity of fluids at lower temperatures, transport of molecules was expected to be much more efficient in forming structure than individual molecular migration through the viscous medium of the fluid.

Gelation Index and Its Relationship with Viscosity - For understanding some of the comparisons in this paper, it is helpful to discuss the relationship between the Gelation Index and viscosity. The value shown by the Gelation Index is related to how rapidly the viscosity changes with temperature over and above its normal exponential interrelationship for hydrocarbons. Thus, a high value for Gelation Index indicates a rapid viscosity change – the more rapid the change, the higher the Gelation Index. At the viscosity level of engine oils at low temperatures, it has been shown that the Gelation Index is directly related to the strength of the structure as indicated by the yield stress of the oil. In general, the more rapid the change in developing structure, the more developed and strong the structure is likely to be – thus, its effect on viscosity.

However, the viscosity of the fluid also plays a major role in the strength of the structure revealed by the Gelation Index. The ability of the micro-crystalline structure to retain some degree of cohesiveness in the face of the stresses applied by the surrounding liquid during flow or, from another viewpoint, the ability of the structure to restrict such flow determines the flow of the combination of liquid and internal structure. Gelation combined with viscosity (properly termed the rheology of the fluid) is what is measured by the SBT. When low levels of viscosity change are associated with high Gelation Indices, it is an indication of the rapid formation of a microstructure having little integrity and, thus, effectively little influence on the viscosity. However, when large changes of viscosity are associated with high Gelation Indices, this is an indication of rapid formation of pervasive, flow-impeding structures of high integrity.

To sum up, it is possible to have low but rapid viscosity changes which can generate high Gelation Indices. In contrast, it is not possible to have high, rapid changes in viscosity without high Gelation Indices although the magnitude of the Gelation Index is not necessarily keyed to the magnitude of the viscosity increase – rather, to the rate of increase caused by gelation.

Application to Jet Fuels - A more specific understanding of low-temperature composition of jet fuels is that the typical JP-8 fuel is a narrow-cut petroleum distillate consisting of less than 20% aromatics with iso-alkanes, cyclo-alkanes, and normal alkanes making up the preponderance of the blend. Studies have shown [8-11] that the low temperature viscosity is dominated by the normal alkanes (more commonly – and significantly – known as simple paraffins). The largest of the n-alkanes (n-C₁₆ to n-C₁₈) begin to crystallize first and their actual concentration determines the ASTM Freeze Point [4]. (Actually, this so-called “freezing point” is the lowest temperature at which crystals remain after formation when the fuel is allowed to warm – thus, it is actually a melting point.)

Jet fuel behaves as a distribution of n-alkanes (n-C₉ to n-C₁₈). The molecules composed of n-C₁₂ or n-C₁₃ have the highest concentration and are dissolved in a mixture of lower-freezing ‘solvent’ hydrocarbons. As jet fuel is cooled, its viscosity gradually increases until a sudden dramatic increase signals the onset of crystallization as already shown in Figures 3, 4, and 5. This sharp gelation point is

somewhat influenced by cooling rate. Faster cooling yields a lower gelation temperature. However, stirring induces a somewhat higher temperature of gelation as a consequence of actively bringing close association of molecules tending to crystallize rather than having to migrate across a relatively viscous liquid in order to associate and crystallize. These two effects were the original hypotheses leading to development of the Scanning Brookfield Technique.

Studies by the University of Dayton Research Institute

The University of Dayton Research Institute's work in this area of concern has been supported under contract by the United States Air Force. Work has been conducted for several years to understand the nature of fuel crystallization and gelation [8-11]. As part of that study, when the prior low-temperature work [6] on jet fuels became more widely known (it was not published), the Scanning Brookfield Technique was brought into the arsenal of attack on the low-temperature fuel flow problem. As mentioned previously, the latter instrument made it possible to directly measure the effects of both viscosity and gelation. In the University of Dayton Research studies, each analysis was conducted at 5°C/hr (instead of the usual 1°C/hr used on lubricants in ASTM D 5133) thus requiring only six hours to perform analysis of samples.

Present Program – SBT Studies of Additive Modification of Low-Temperature Flow

The work reported in this paper, was directed toward additive improvement of the low-temperature flow properties of jet fuels. Specifically, the focus of the work was to find if structure modifying additives could improve the low-temperature characteristics of Jet A-1 fuels. Companies who previously had shown considerable ability to develop additives effective in improving the low-temperature flow properties of lubricants were encouraged to develop candidates to similarly improve the low-temperature properties of jet fuels.

Results

Viscometer Calibration at Very Low Temperatures

The use of the Scanning Brookfield Technique at very low temperatures required not only the calibration of special Tannas/Brookfield viscometer heads but the development of new reference fluids, first by the University of Dayton Research Institute and then by the Savant Laboratories. The former used a chemically pure lower molecular weight alcohol while the latter developed a narrow molecular weight mineral spirit hydrocarbon.

Figure 6 shows calibration of a viscometer head using the alcohol reference fluid. Several observations pertaining to the data can be made.

First of all, the calibration curve shows excellent linearity with a Coefficient of Determination value, R^2 , of 0.99998 (1.0 being perfect correlation).

Secondly, the viscosity range covers the range of interest and thirdly, the temperature range similarly covers the range of concern. It will be noted that the abscissa (X-axis) intercept is near to, but not exactly, zero. This may reflect either some slight but constant and measurable mechanical friction or a spring tension offset in the viscometer head. All in all, the data show the precision with which the viscosities and gelation of jet fuels can be measured.

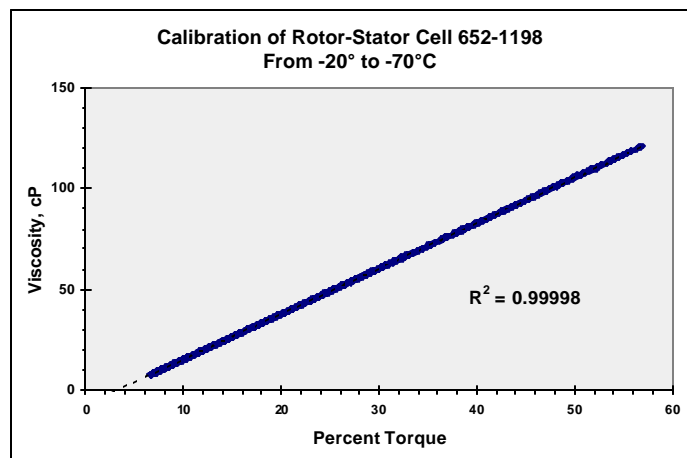


Figure 6 - Tannas TAV-1 viscometer head calibration using a University of Dayton reference fluid

Investigations of Jet Fuel Flow Modification – Untreated Jet Fuels

Jet A Fuel 1 - Figure 7 shows results with one of the Jet A fuels investigated. The fuel does not show the sharp flow break of the fuels studied earlier by Selby and Müller [6]. Instead, the viscosity-temperature flow curve has several shifts in viscosity and finally rises in viscosity at a more gradual rate. The Gelation Index curve reflects this by a series of peaks indicating periodic increases in the gelation. These changes are believed caused by the agglomeration of gel or crystalline structures which, in turn, reflect the transition of fuel components soluble from a soluble state into an insoluble state.

The major change in the viscosity-temperature curve at about -49°C is shown by the Gelation Index peak of 67 although this is preceded by a 'transition zone' of linked smaller peaks occurring between -46° and -48°C shown in Figure 7. An earlier pair of gelation peaks and a smaller transition zone is shown from -42° to -43.5°C about 5° to 7°C above the major peak.

It is interesting and significant that the ASTM Freezing Point at -43.5°C (also shown in Figure 7 – which is actually the rising temperature at which all visible crystals disappear), occurs near the temperature of an early Gelation Index peak. This suggests that the ASTM Freeze Point associated with crystal appearance and disappearance is strongly linked to the information from Gelation Index curve. Moreover, a prior peak in the Gelation Index curve, at about -42°C indicates that visible crystal formation or disappearance is only one aspect of gelation. The cause of this earlier peak may be non-visible formations of proto-structures or liquid crystals.

Jet A Fuel 2 – Figure 8 shows the SBT analysis of a second Jet A fuel. This second Jet A fuel shows somewhat sharper response to the onset of major gelation. However, after this period of gel formation (shown by the Gelation Index of 131 at a temperature of -46°C), again shows the more gradual rise in viscosity with decreasing temperature previously seen in Figure 7.

Again, the Freezing Point at -41.5°C is associated with a small Gelation Index peak and again this latter peak is preceded and followed by other small peaks. From both Figures 7 and 8 it would seem that the Freezing Point is preceded by visually unseen occurrence of gelation. In this fuel, the separation of the main gelation peak and those peaks at higher temperatures is about 4°C . The data also show that the Freezing Point is about 4° to 5°C above the point of relatively rapid change of viscosity. It will be noted that after the sudden rise in viscosity, the viscosity-temperature curve resumes an exponential relationship typical of the viscosity-temperature relationships of the heavier hydrocarbons in lubricants and, as a consequence, the Gelation Index curve drops to a low value and becomes relatively flat.

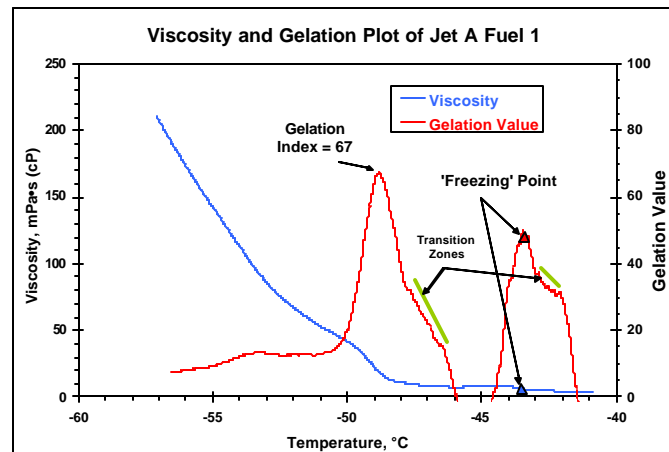


Figure 7 – SBT analysis of Jet A Fuel 1

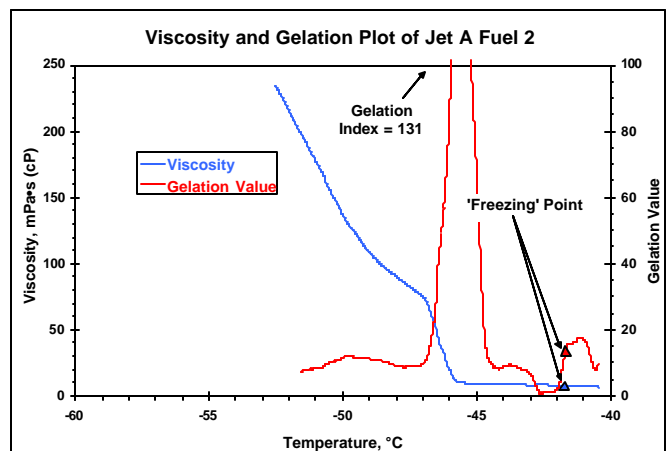


Figure 8 - Analysis of Jet A Fuel 2

Jet A-1 Fuel 3 - Figure 9 shows results with a fuel of the Jet A-1 class having an obviously improved low-temperature operation range. down to -51°C . However, the viscosity break is very sharp and large at -52°C and the Gelation Index shows the high values associated with massive and rapid gelation/crystallization. In this respect, the fuel is similar to the responses of the jet fuels analyzed in earlier work shown in Figures 3, 4, and 5.

Specifically, the fuel's molecular composition generates a strong gelation structure that rapidly increases the viscosity to the point where it drives the viscometer off scale with no recovery of the Gelation Index curve as was seen in Figure 3. That is, it would appear that the fuel has ostensibly become solid regarding further flow.

Jet A-1 Fuel 4 - A second fuel of the Jet A-1 class is shown in Figure 10. This fuel is considerably different in response to analysis than Jet A- Fuel 3. First of all, Fuel 4 shows that the amount of gelation contributing to the Gelation Index is more limited than Fuel 3 - gelation of the fuel is evident but not overwhelming. In fact, after the gelation has contributed about 150 cP of viscous resistance to flow, the viscosity-temperature relationship again becomes exponential and the exponential derivative takes a more horizontal cast.

Jet A-1 Fuel 5 - SBT analysis of a third fuel of the Jet A-1 class is shown in Figure 11. Again the viscosity break is abrupt but, as shown by the Gelation Index curve, recovers the beginning of an exponential viscosity-temperature relationship. However, the relationship indicates a rapid change of viscosity with temperature suggesting that gelation/crystallization is going on rapidly but that the gelation mass is not cohesive and still flows in a fluid-like manner.

General Observations of Jet A-1 Oils Tested - It is evident from the Figures 9, 10 and 11 that considerable differences exist among these Jet A-1 fuels particularly regarding Gelation Indices. However, the three fuels all have levels of gelation sufficient to test the ability of flow-modifying additives.

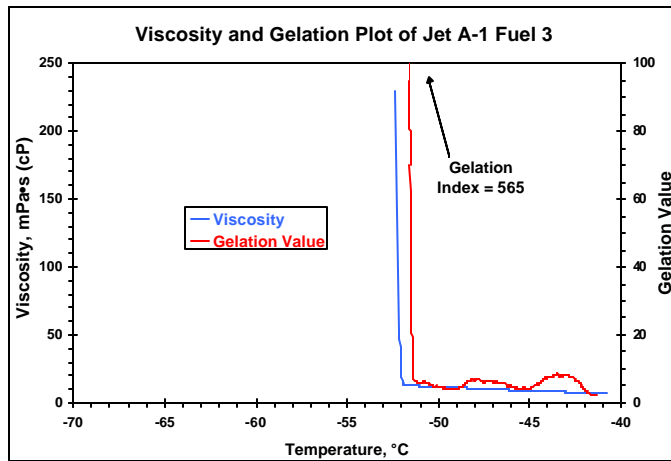


Figure 9 – Scanning Brookfield Technique analysis of Jet A-1 Fuel 3

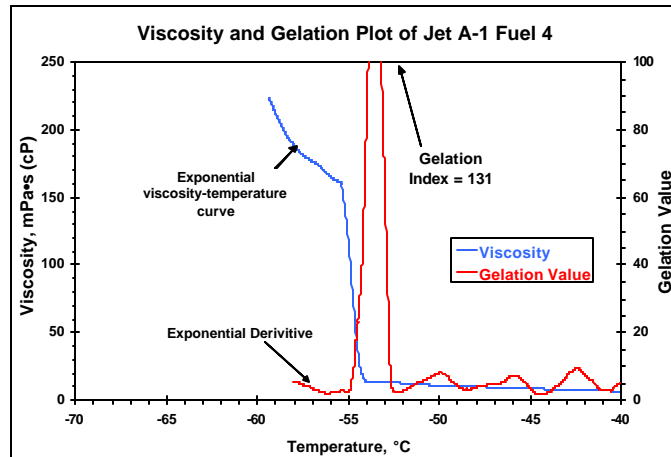


Figure 10 – Scanning Brookfield Technique analysis of Jet A-1 Fuel 4

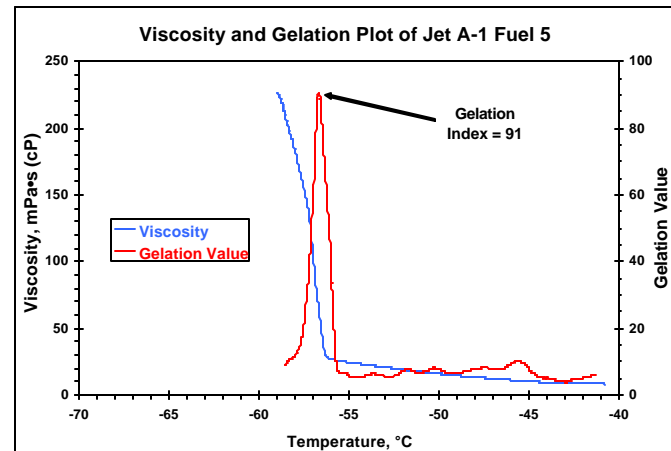


Figure 11 - Scanning Brookfield Technique analysis of Jet A-1 Fuel 5

Investigations of Jet Fuel Flow Modification – Treated Jet A-1 Fuels

Two different additives, both at 0.5% treatment level, were used to determine whether and to what extent the characteristics previously shown in Figures 9, 10, and 11 could be modified.

Additive Treatment Effects on Jet A-1 Fuel 3 – The two additive treatments were applied to Fuel 3 with the results shown in Figures 12 and 13.

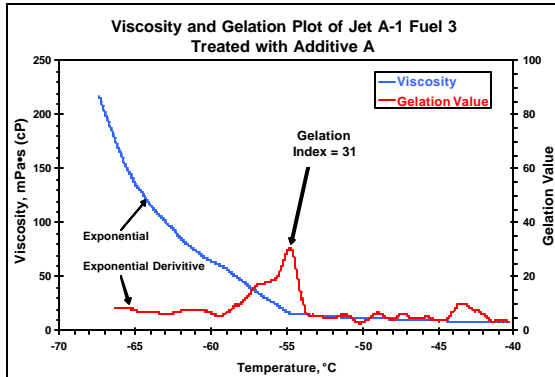


Figure 12 – Effects of Additive A in Fuel 3

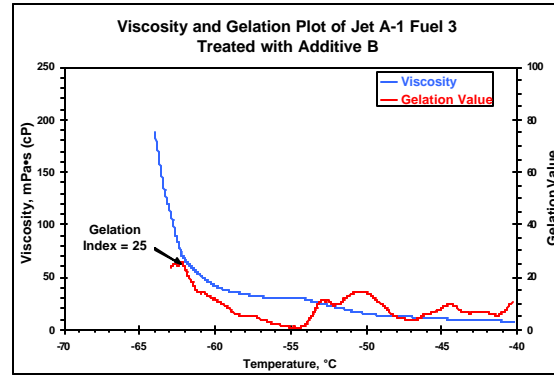


Figure 13 – Effects of Additive B in Fuel 3

Effects of Additive A on Fuel 3 - Comparing Figure 12 with Figure 9 shows significant change in the flow characteristics of Fuel 3. The sharp rise in viscosity accompanying gelation shown in Figure 9 has been eliminated. Interestingly, while there still is a gelation peak using Additive A, it is much smaller and has been moved from -52° to -55° C. Moreover, it should be noted that the viscosity-temperature curve -- which usually initially shows an exponential change -- resumes the exponential form after the gelation peak. This is noted in Figure 12 and is confirmed by the essentially horizontal, Gelation Index curve. Essentially then, Jet A-1 these data indicate that Fuel 3 has been converted into a fuel of much more acceptable flow characteristics capable of serving the aircraft at more than 15° C lower temperatures than its non-treated form and suitable for the rigorous conditions of high altitude, long range, fuel efficient operations.

Effects of Additive B on Fuel 3 – Comparing Figure 13 with Figure 9, results are evidently different than those of Figure 12. Additive B affects the viscometric and gelation tendencies differently. No significant gelation peak shows until late in the analysis at which point both the viscosity-temperature curve begins to rise more sharply than the normal exponential expression. Concomitantly, the Gelation Index curve also increases and shows the development of some gelation. Still, the SBT data indicate that the fuel is suitable for use at temperatures well below that at which the untreated oil will congeal.

Additive Treatment Effects on Jet A-1 Fuel 4 – When the two additive treatments were applied to Fuel 4, the results in Figures 14 and 15 were generated.

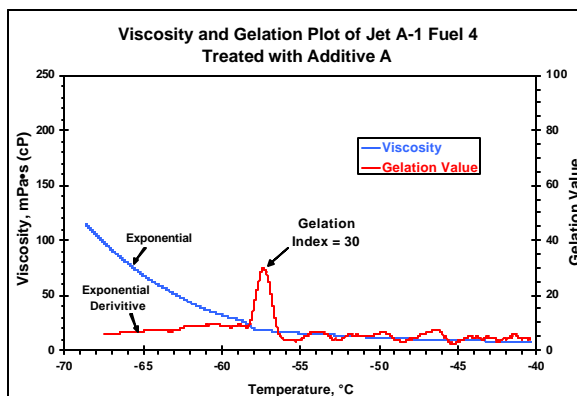


Figure 14 – Effects of Additive A in Fuel 4

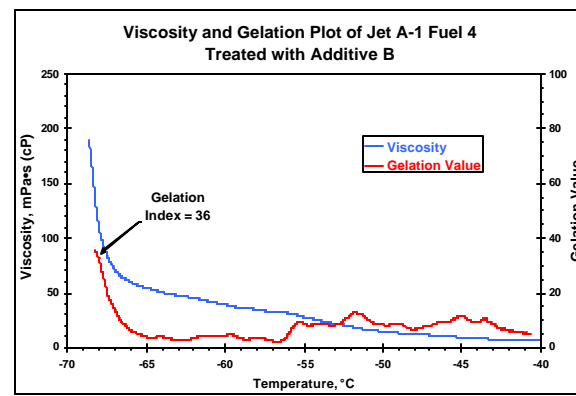


Figure 15 – Effects of Additive B in Fuel 4

Effects of Additive A on Fuel 4 – Comparing Figure 14 with Figures 10 and 12 it is evident that the effects of Additive A are quite pronounced in both and that the milder gelation tendencies of Fuel 4 in comparison with Fuel 3 has generated an even more acceptable viscosity-temperature curve. Gelation tendencies are marginal with the exception of the comparatively small Gelation Index peak of 30 at -58°C after which the gelation curve drops and flattens. Essentially, the viscosity-temperature becomes that of non-gelation-forming hydrocarbons and thus an apparently significant transition from a class Jet A-1 to a much more gelation resistant fuel down to -68°C and, most likely, even lower.

Effects of Additive B on Fuel 4 – Figure 15 differs from Figure 14 in that the Gelation Index peak is eliminated but, as in Figure 13, at lower temperatures the viscosity begins to rise more quickly than would be expected from the simple exponential viscosity-temperature relationship. This is also reflected by the rise in the Gelation Index curve which reaches a value of 28 before the viscosity of the fuel exceeds the capacity of the viscometer. The resulting fuel flow characteristics are clearly an improvement in comparison to the untreated Fuel 4 shown in Figure 10 but Additive B cannot be said to have transformed Fuel 4 as well as Additive A.

Additive Treatment Effects on Jet A-1 Fuel 5 – Figures 16 and 17 show results of the additive treatments of Jet A-1 Fuel 5. From Figure 11, this fuel is the one with lowest Gelation Index – a value of 91 at -57°C – and thus the fuel with lowest structure-forming capability.

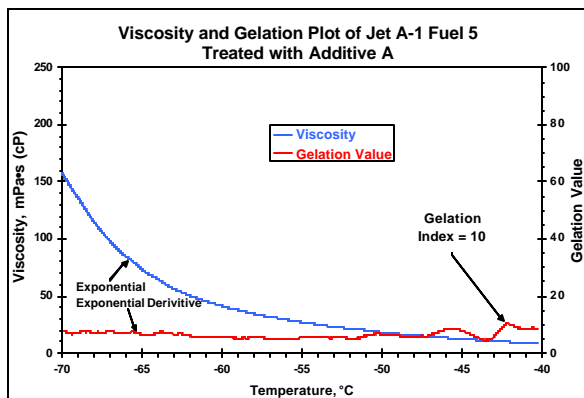


Figure 16 – Effects of Additive A in Fuel 5

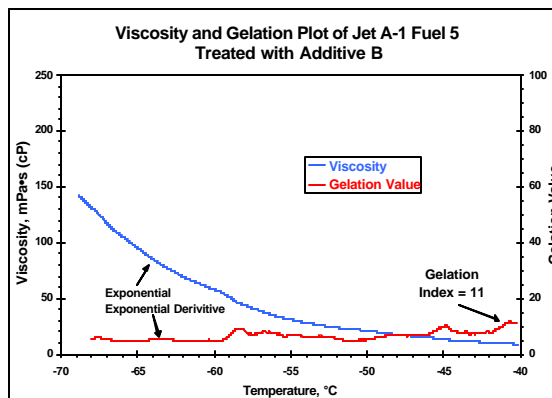


Figure 17 – Effects of Additive B in Fuel 5

Effects of Additives A and B on Fuel 5 – The information on both Figures 16 and 17 indicate that Fuel 5 is very susceptible to the effects of both additives. The viscosity-temperature curves are both exponential with no evidence of significant Gelation Indices. In fact, both of these fuels now behave as though they were essentially free of any gelation tendencies and demonstrate excellent low-temperature flow down to -70°C . Both of these fuels would seem to make highly desirable fuels for all flight conditions.

Discussion

Findings and Implications of the Study

The need to have jet fuels that can perform in the low-temperature environment required for high altitude or very cold ambient temperature flight is self-evident. It is highly desirable to measure, understand, and remove, if possible, any limitations that these fuels may impose on aircraft operation as a consequence of any gelation/crystallization tendencies at the low temperatures frequently encountered in high altitude flight.

Findings - A relatively short bench test called the Scanning Brookfield Technique has shown that all jet fuels tested to date have shown significantly high structure-forming tendencies that clearly limit their ability for use at high altitudes or low ambient temperatures.

Scanning Brookfield Technique (SBT) - A test developed and used widely for testing automotive lubricants for use at low temperatures has been demonstrated to have the ability to continuously determine both the flow and the gelation tendencies of jet fuels over any desired low-temperature range.

This six-hour bench test scans the flow and gelation behavior of a jet fuel over the temperature range of interest and up to eight tests can be run simultaneously in the same instrument. The SBT has been found a simple, direct method of measuring the complex flow properties of jet fuels. That is, a single SBT determination shows both the viscosity change with decreasing temperature as well as a clear “fingerprint” of the occurrence and magnitude of the occurrence and effect of gelation on viscosity is revealed.

The Problem of Low-Temperature Flow and Limiting Use of Jet Fuels - Presence of gelating/crystallizing tendencies in jet fuels is very common as shown by the SBT studies reported in this paper and earlier work. All the fuels used in the present studies and in previous studies showed evident gelation tendencies. Moreover, it was found that formation of serious fuel flow restriction at high altitudes was more critical for Jet A-1 fuels which are specifically made for lower temperature operation. That is, as the jet fuels are refined to gain a few degrees of low temperature operation, the occurrence of strong gelation/crystallization is more abrupt and critical.

The studies, conducted from -40° to -70°C were very explicit in showing the flow problems carried by the jet fuels examined which were of the Jet A and, particularly, Jet A-1 classes. Sharp rises in viscosity and gelation were particularly evident in jet fuels of the Jet A-1 classification. In these cases, a change of hundreds of centiPoise viscosity could occur within as little as 1°C decrease. Such an occurrence in flight would most certainly cut off fuel flow to the engines.

The particular focus of the study was to determine whether flow modifiers of the type frequently used in lubricants would be effective in improving the response of the Jet A-1 fuels. Two such additives were studied at levels of 0.5% concentration and it was found that

1. Such additives have a dramatic effect on the flow characteristics of these jet fuels.
2. The two additives had different effects on the fuels.
3. Different sources of fuels affect the degree of changes brought by the additives.

On the basis of the present data, it may be unequivocally stated that low-temperature fuel flow and temperature range of use can be improved significantly by the incorporation of additives interfering with the development of gelation and congealing of the fuel.

Implications - The implications of this study are that

- A simple bench test method of flow and gelation such as the Scanning Brookfield Technique should be used to determine the low-temperature flow response and performance limitations of jet fuels used in commercial and military aircraft.
- Further studies of increased urgency should be made of additives capable of modifying the low-temperature performance of jet fuels.
- Simplistic tests such as cloud point, pour point, Specification Freeze Point, etc. do not measure the actual low-temperature rheological properties of fuels affecting flow behavior of fuels under operational conditions.
- The variations found among the jet fuels tested in this and earlier studies strongly suggest that jet fuels may vary widely around the world in their ability to be pumped at the low-temperatures frequently encountered in longer, high altitude flights.

Conclusions

In view of the findings of this study it is concluded that present methods of determining and limiting the low-temperature use of jet fuels are limited and/or ambiguous and may in many cases be unnecessarily limiting to the use of such fuels.

Additive treatment, which has been shown to significantly modify the low-temperature flow properties of jet fuels, should be intensively studied as a means of improving jet fuel low-temperature properties.

The Scanning Brookfield Technique -- a direct and informative test for determining the low-temperature flow and gelation/crystallization characteristics of jet fuels -- should be applied to study jet fuels around the world as a matter of considerable concern and value.

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