Instrumental Approach and Improvement of the Low-Temperature Determination of ATF Fluidity

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Abstract

Measurement of the low-temperature viscometric characteristics of automatic transmission fluids and gear oils has been conducted in an air bath environment for several decades despite certain limitations of precision in such an environment. The present paper discusses the background of the method, its past limitations and the means by which they were overcome.

History and Introduction

ATF Rheology at Low Temperatures

Low-temperature studies by automobile manufacturers started in the 1950s as a consequence of the failure of automatic transmissions in low-temperature conditions. Cold room studies and bench correlation showed that these failures were caused by the inadequate flow of automatic transmission fluids **[1]**. In turn, the inadequate flow was caused by the wide-spread use of extrapolated viscosities determined at temperatures of 100° and 210°F (37.8° and 99°C, respectively) by the empirical MacCoull **[2]** and Walther **[3]** viscosity-temperature equation. Interpolation and short extrapolation to higher temperatures work well with this equation but the assumption that extrapolation could be made to considerably lower temperatures was shown to be in serious error when the viscosities of these ATFs were actually measured at the low temperatures of automatic transmission operation.

The Low-Temperature Brookfield Method – With the availability of a temperature-controlled refrigerated cold chest and a rotational Brookfield viscometer, studies began on automatic transmission fluids in 1954.

A simple 260 mm by 24 mm test tube was chosen as a stator as well as a thin rotor-spindle selected made by Brookfield Engineering for their LVT viscometer head. The active portion of the rotor in contact with the fluid had the dimensions of a cylinder 3.2 mm in diameter by 57.2 mm in length. The purpose of choosing such a narrow rotor was to considerably reduce the stator wall effect and essentially eliminate the need for rigorous rotor-stator alignment. This viscometric cell developed for the air bath is shown in Figure 1.

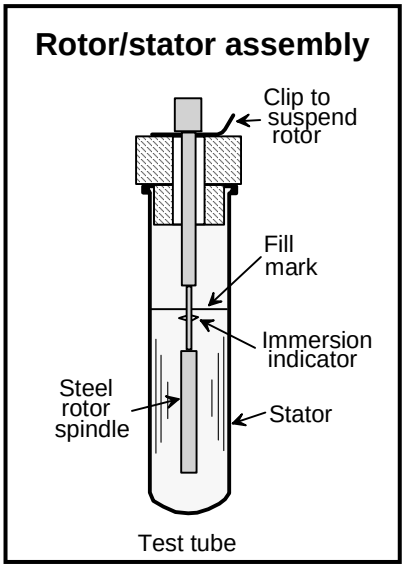

Fig. 1 – Cutaway sketch of rotor-stator cell.

As mentioned, results of this study **[1]** showed good correlation with the low-temperature failure of automatic transmissions in both the field and cold-room as a consequence of not being able to pull the ATF rapidly enough into the transmission pump to develop sufficient pressures to prevent slippage of the transmission clutch plates.

Low-Temperature Viscometry Specifications Using the Brookfield Method – As a consequence of this study, a method for determining the low-temperature rheology of ATF was first made into specifications by OEMs, then written in a cooperative CRC Report, and finally, in 1971, submitted and accepted by ASTM Committee D02 as Method D2983 entitled "Low-Temperature Viscosity of Automotive Fluid Lubricants Measured by Brookfield Viscometer" **[4]**. Later, the method was applied to gear oils and hydraulic fluids.

Low-Temperature Brookfield Method

Test Cell – As shown in Figure 1 by the fill line, about 30 mL of the sample was placed in the test tube stator and a wooden stopper, with a vertical hole in the center, was placed in the mouth of the test tube. A stainless steel spindle-rotor was inserted through this hole and suspended with a clip so that the rotor was sufficiently below the surface of the fluid such that fluid contraction with cooling would not drop below the immersion indicator of the rotor.

Balsa Block Carrier – To minimize sample heating when the sample was removed from the air bath and transferred to the viscometer for measurement, a balsa block carrier shown in Figure 2 was developed.

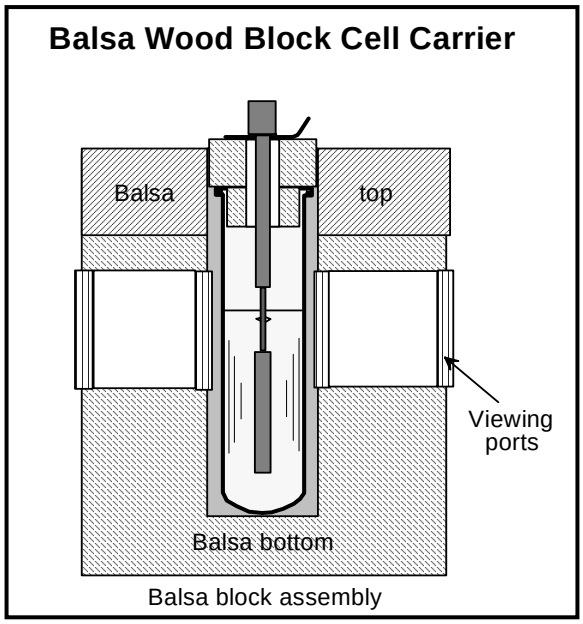

Fig. 2 – Balsa wood cell carrier.

Test Protocol – The air bath was set for, and cooled to, the desired final temperature (for example, -40°C) and placed under temperature control. At that point, a number of cell assemblies containing the samples were put into a rotating rack permanently stationed within the air bath. (The purpose of the rotating rack was to assure equal exposure of the cells to the variations of temperature within the air bath as the air was circulated.)

Choice of Rotor Speed – Brookfield viscometer heads are capable of multiple speeds. As a consequence of sample warming (which took place despite the balsa carriers), the quickest mode of analysis was to start at highest rotor speeds which would usually exceed the torque capacity of the viscometer head. In such case, the rotation rate of the rotor was then reduced step-wise until a viscosity value was measurable. Moreover, the highest viscosity value was always taken since sample warming would reduce the viscosity relatively quickly.

Need for Double Samples – As a consequence of the sample warming that took place while searching for the maximum speed permitting viscosity measurement, it became the practice of running two samples of the same oil with the first analysis showing the rotor speed required and permitting the second sample immediately set to this speed to gather the highest viscosity. The two values were not averaged.

Problems Associated with the Air Bath Method

Sample Warming and Precision – As a consequence of the exponential effect of temperature on viscosity, limitations brought by the air bath approach have been primarily associated with sample warming in the transfer and measurement procedure.

Alternative Methods of Cooling

Sample Cooling Rate in an Air Bath – Figure 3 shows the cooling rate of an ATF sample in an air bath using the cell shown in Figure 1. It is this rate which must be emulated in any alternative cooling approach.

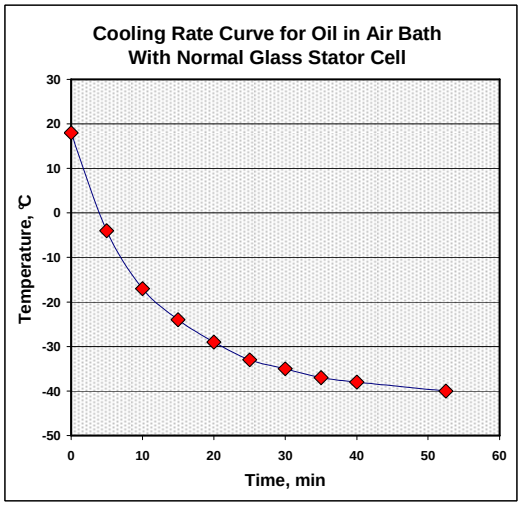

Fig. 3 – Cooling rate of test oil in air bath.

Air-bath cooling a lubricant sample in the cell shown in Figure 1 is dependent on three factors:

1. Rate of heat passage through the glass wall to the impinging air molecules,

2. Rate of heat passage to the flowing air through the sample to the glass cell wall of the stator through any viscous or rheological impediments, and

3. Rate of cooling of the sample-heated circulating air by refrigeration system.

Obviously, these three factors can be considerably different in a liquid bath in which case there is much more heat-drawing ability of the greater numbers of liquid molecules impinging on the exterior stator surface.

Sample Cooling Rate in a Liquid Bath – Figure 4 shows the cooling rate of an oil sample in a liquid bath held at -40°C in contrast to the air-bath cooling profile shown in Figure 3.

As previously mentioned, the comparatively rapid cooling rate is an expected consequence of direct liquid bath contact with the exterior stator wall.

Acceptable Liquid Bath Approaches – Recognizing the difficulty of cooling the sample at the rate shown in the air bath, one of the first approaches was to transfer the samples from an air bath to a liquid bath held at the final temperature of analysis. This had the dual benefit of proper cooling rate in the air bath with constant temperature of analysis in the liquid bath.

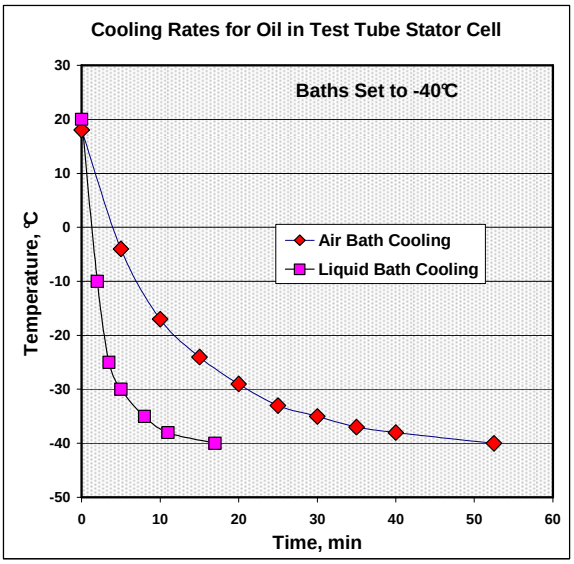

Fig. 4 – Direct liquid cooling of air-bath stator in liquid bath.

The deficiency in this approach was that the two baths needed both the floor space required by the air bath as well as the bench space of the liquid bath plus floor or bench space for the refrigeration mechanism.

Programmable Liquid Baths – Another approach was to cool the samples in a liquid bath programmed to emulate the cooling curve of an air bath.

Programmable baths capable of emulating the initial cooling rate in the air bath with a decrease in the temperature of the bath cooling medium of -40°C in 10 minutes demands a large refrigeration source. Such rapid cooling of a liquid bath imposes considerable temperature variation in the bath coolant during cooling but especially during the more rapid portions of the cooling process. However, programmed cooling is certainly another approach and avoids the limitations of the air bath regarding temperature control of the samples. Batch processing of samples is, however, still required.

Direct Air Bath Simulation in a Liquid Bath

An Air-Bath Emulating Stator Cell

The Dewar Cell – The three factors controlling heat transfer in the air bath discussed previously were met by

1. Reducing heat transfer of the test fluid in the stator cell to the liquid bath by interposing a surrounding Dewar section filled with sufficient gas to emulate heat transfer in the air bath,

2. This forgoing control of heat transfer naturally controlled the rate of heat transfer through the sample.

3. The rate of cooling of the gas in the Dewar section is always determined by the same temperature-influenced 'heat-conveyor' generated by Brownian motion of the gas molecules in the Dewar section.

The concept was found patentable **[5]** and the Dewar sectored stator cell was trade-named the SimAir® stator cell.

Figure 5 shows a sketch of the special Dewar-sector stator cell.

It will be noted that the assembled cell uses a composite plastic rotor to prevent the rotor from warming the sample. The Dewar section extends above the fluid sample. The plastic collar also blocks warm air from entering the interior of cooling stator.

Cooling Rate with Dewar Stator – Table 1 and Figure 5 show the cooling curve obtained in the SimAir® stator cell compared to that of the air bath cooling curve.

Table 1 -- Cooling rates of oil sample

Air Bath Normal Stator		Liquid Bath SimAir™ Stator	
Time, min.	Temp. ℃	Time, min.	Temp. ℃
0	18	0	21
5	-4	5	-3
10	-17	10	-14
15	-24	15	-22
20	-29	20	-28
25	-33	25	-32
30	-35	30	-34
35	-37	35	-37
40	-38	40	-38
52.5	-40	46.5	-40

It is evident that the Dewar-sectored, SimAir® stator in a constant temperature liquid bath closely matches the cooling rate of the normal stator in a constant temperature air bath (in this case when both baths are held at -40°C).

It should be noted that in collecting the cooling rate data from the SimAir® stator, it was important the thermocouple sensor was made from very fine, insulated wires to prevent heat from entering the cell down the sensor. In addition it should be noted that only composite plastic spindles should be used with the SimAir® stator to prevent any source of heat entering the interior of the stator. Insulated spindles are required by ASTM D2983 in any use of a liquid bath.

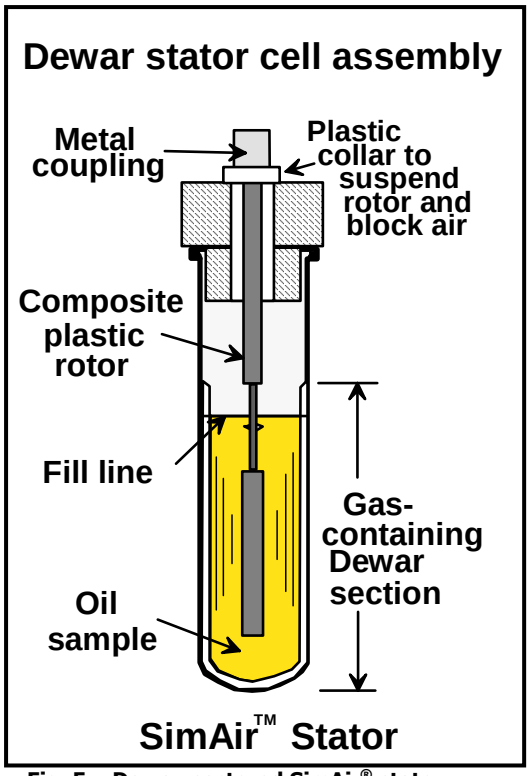

Fig. 5 – Dewar-sectored SimAir® stator.

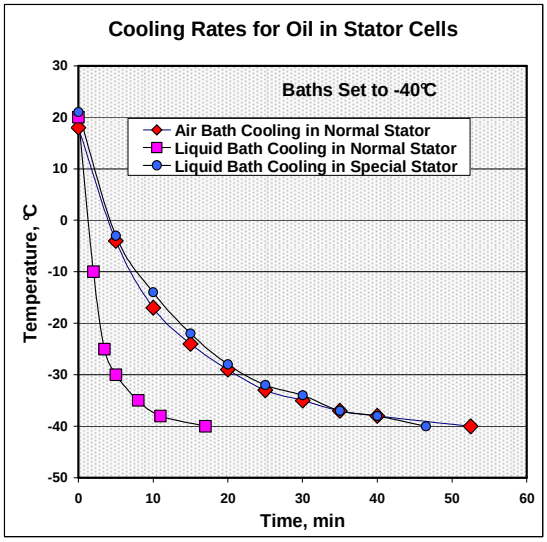

Fig. 6 – Comparison of cooling rates of air-bath and liquid baths with and without the use of the Dewar-sectored SimAir™ stator.

Discussion

Value of a Mechanism-Correlated Method

Use of the original Brookfield low-temperature method through almost a half century is evidence of the significance of methods that have been developed to correlate with mechanical devices – in this case the automatic transmission performance at low temperatures. Once this correlation has been established the bench method has continuing utility in providing information on the rheology of oils and fluids at these temperatures. Although other low-temperature methods of measuring rheology have since been developed, they have not replaced this well-practiced and distributed test.

The continued practice of this test has not been diminished by some of its difficulties when using air baths:

- Relatively imprecise temperature control and heat distribution in cold-air baths.
- Some degree of difficulty in the transfer and temperature control of samples in obtaining viscometric values.
- Need for duplicate samples to assure rapidly obtaining proper rotor speeds before the data was compromised through sample warming.
- Need to run batches of samples at a time.

Impact of New Approaches

Liquid Baths – Efforts to use more precise temperature-controlling liquid baths to hold the sample at the desired temperature after air-bath cooling was a significant improvement but still required sample cooling in an air bath.

In comparison, use of programmed liquid baths to emulate the cooling of the samples in an air bath required sizeable refrigeration units to handle the first ten minutes of emulating an air bath set at, for instance, -40°C. Temperature control in different sections of the liquid bath was also a factor to be considered requiring high bath agitation to distribute this coolant. Again, however, it was a step forward in the method

Emulation of a Method

Liquid baths have much to recommend their use in low-temperature viscometry and rheology. However, the latter property of a mineral oil-based fluid is frequently highly dependent on the way in which the fluid sample is cooled. Simply cooling the fluid is not enough – cooling it in the proper manner can make a considerable difference in results.

In the case of the low-temperature Brookfield method, emulation of the cooling curve was found important as a result of the need to replicate rheological development in the fluids. In some cases the fluids could set up some degree of a gelated structure which imposed greater difficulty for the transmission pump to draw in such ATF.

Emulation of air cooling is a direct function of controlling the heat transmission from the sample to the cold source. In the case of a liquid cold bath, the rate of heat transfer must be controlled to that occurring in the air bath and it was this recognition resulted in the Dewar-modified SimAir® stator and the results shown in this paper.

Essentially, the development and use of the Dewar-sectored stator has simultaneously resolved three of the four problems accompanying the used of ASTM method D2983.

End of the Need for Batch Analyses

In the practice of the use of the Dewar-sectored stator for low-temperature Brookfield analyses, it was recognized that the fourth problem mentioned earlier of need to run ATF and gear oil analyses in batches was also eliminated.

The Dewar-sectored SimAir® stator cell has shown another advantage in that it is no longer necessary to run a set of analyses at the same time. Rather a fluid sample in the SimAir® stator cell can be inserted in a liquid bath that is held at the desired temperature at any time desired and simply analyze the sample 16 hours later. This increases throughput of analyses and more productive use of the Brookfield method since the liquid bath can be kept continuously in use.

Precision Studies

Precision of the Brookfield method using the Dewar-sectored SimAir® stator cell is presently being studied and, thus far, seems to have been improved by this technical development.

Acknowledgements

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patiently gathered the data involving normal single-wall and Dewar-sectored SimAir® stators which prefaced the latter stator's development and introduction to the technical field; Mr. Gregory Miiller who has worked closely with, and provided information, thought, and gentle challenges to the author over nearly 20 years of association.

Lastly, but firstly, he would like to acknowledge the firm, understanding, and continuing support of Mrs. Jean Gale Selby, his wife, during his years of transition from a young physical chemist at General Motors Research Laboratories and beyond.

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