In recent years, some large lubricant marketers have run advertisements on TV that highlight the importance of viscosity breakdown. These advertisements make it seem like viscosity is a complex chemical property of the fluid, when in fact it is a measurement of a physical property. Simply stated, viscosity is a measure of a fluid's internal resistance to flow. A good example of this was provided in one of the TV adverts, which showed two oils being cooled until one continued to flow out of the bottle readily, while the second dropped out in blobs. The resistance to flow, or viscosity, of the second oil had increased dramatically with the decrease in temperature. This advert illustrated just how important it is to consider viscosity when choosing the proper lubricant for a specific application.

The presence of viscosity information on almost all lubricant marketers' technical literature is an indication that it is also important in the marketing of lubricants. Original equipment manufacturers often specify the lubricant to be used in their equipment by product type and viscosity. Lubricant marketers usually sell their lubricants

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SHEDDING LIGHT ON **LUBRICATION VISCOSITY**

according to specific viscosity grades, such as SAE 15W40, ISO 46 and AGMA 3.

It is clear that – for the majority of the players in the lubricant industry – the proper viscosity of a fluid is the most important attribute in proper lubrication. There are several reasons for this, including, but not limited to:

- Viscosity affects fluid film thickness under certain conditions of temperature and load in lubrication applications.
- Viscosity affects heat generation and removal in bearings, cylinders and gears.
- Viscosity determines the ease with which machines can be started in low-temperature conditions or can be kept running in high-temperature conditions.
- Viscosity can be used to control a fluid's sealing ability, which results in lower consumption.

Viscosity defined

As mentioned above, viscosity is a physical measurement of a fluid's internal resistance to flow. Assume that a lubricating fluid is compressed between two flat plates, creating a film between the plates. Force is required to make the plates move, or overcome the fluid's film friction. This force is known as dynamic viscosity. Dynamic viscosity is a measurement of a lubricant's internal friction and it is usually reported in units called poise (P) or centipoise (cP), (1 P = 100 cP). A common tool used to measure dynamic viscosity is the Brookfield viscometer, which employs a rotating spindle that experiences torque as it rotates against fluid friction.

A more familiar viscosity term is kinematic viscosity, which takes into account the fluid density as a quotient of the fluid's dynamic viscosity and is usually reported in stokes (St) or centistokes (cSt), (1 St = 100 cSt). The kinematic viscosity is determined by using a capillary viscometer in which a fixed volume of fluid is passed through a small orifice at a controlled temperature under the influence of gravity.

Grease viscosity, traditionally called consistency, cannot be measured using the tests noted above. However, it is still important to select the correct grease for each specific application. Greases are fluid lubricants enhanced with a thickener to make them semi-solid. They are usually

Table 1. SAE J300 viscosity grades for engine lubricants[1]

SAE viscosity grade	Low-temp (°C) cranking viscosity, cP maximum	Low-temp (°C) pumping viscosity, cP maximum with no yield stress	Kinematic viscosity (cSt) at 100 °C maximum	Kinematic viscosity (cSt) at 40 °C maximum	High shear viscosity (cP) at 150 °C minimum
0 W	3250 @ -30	60 000 @ -40	3.8	-	-
5 W	3500 @ -25	60 000 @ -35	3.8	-	-
10 W	3500 @ -20	60 000 @ -30	4.1	-	-
15 W	3500 @ -15	60 000 @ -25	5.6	-	-
20 W	4500 @ -10	60 000 @ -20	5.6	-	-
25 W	6000 @ -5	60 000 @ -15	9.3	-	-
20	-	-	5.6	< 9.3	2.6
30	-	-	9.3	< 12.5	2.9
40	-	-	12.5	< 16.3	2.9*
40	-	-	12.5	< 16.3	3.7**
50	-	-	16.3	< 21.9	3.7
60	-	-	21.9	< 26.1	3.7

* For 0W40, 5W40 and 10W40 grades

** For 15W40, 20W40, 25W40 and 40 grades

Table 2. SAE J306 viscosity grades for axle and manual transmission lubricants[2]

SAE viscosity grade	Maximum temperature for viscosity of 150 000 cP °C	Viscosity at 100 °C cSt minimum	Viscosity at 100 °C cSt maximum
70 W	-55	4.1	-
75 W	-40	4.1	-
80 W	-26	7.0	-
85 W	-12	11.0	-
80	-	7.0	< 11.0
85	-	11.0	< 13.5
90	-	13.5	< 18.5
110	-	18.5	< 24.0
140	-	24.0	< 32.5
190	-	32.5	< 41.0
250	-	41.0	-

used in applications where a liquid lubricant would run out. Greases are sold by consistency grade, which in this case will be used synonymously to viscosity grade. Grease consistency is measured using the cone penetration test (Figure 3). The National Lubricating Grease Institute (NLGI) created grade ranges for greases that have become the industry standard. These ranges characterise the flow properties of greases.

Viscosity considerations

Various conditions must be considered when specifying the proper viscosity of a lubricant for a given application. These conditions include the operating temperature, the speed at which the specific part is moving, and the load placed upon the part. One other consideration is whether or not the lubricant can be contained so that it remains present to lubricate the intended moving parts.

Temperature

The viscosity of a lubricant changes with temperature: in almost all cases, as the temperature increases, the viscosity decreases and – conversely – as the temperature decreases, the viscosity increases. To select the proper lubricant for a given application, the viscosity of the fluid must be high enough that it provides an adequate lubricating film, but not so high that friction within the lubrication film is excessive. Therefore, when a piece of equipment must be started or operated at either temperature extreme (hot or cold), the proper viscosity must be considered.

Speed

The speed at which a piece of equipment operates must also be considered when specifying the proper lubricant viscosity. In high speed equipment, a high viscosity lubricant will not flow well in the contact zones and will channel out by fast-moving elements of the equipment. On the other hand, a low viscosity lubricant would have too low a viscosity to properly lubricate slow-moving equipment, because it would run right out of the contact zone.

Load

Equipment loads must also be considered when selecting the proper lubricant viscosity. Under a heavy load, the lubricant film is squeezed or compressed. Therefore, a higher viscosity lubricant is needed. The higher the viscosity, the more film strength the lubricant will generally possess. In addition, the load can be either a continuous or shock load. A continuous load is a steady load that is maintained while the equipment is operational, while a shock load is a pounding or non-steady load. Under shock-load conditions, a low viscosity lubricant would not possess enough film strength to stay in place, whereas a

Table 3. ISO viscosity grades for industrial oils[3]

ISO viscosity grade	Kinematic viscosity at 40 ˚C, minimum cSt	Kinematic viscosity at 40 ˚C, maximum cSt
2	1.98	2.42
3	2.88	3.52
5	4.14	5.06
7	6.12	7.48
10	9.00	11.0
15	13.5	16.5
22	19.8	24.2
32	28.8	35.2
46	41.4	50.6
68	61.2	74.8
100	90.0	110
150	135	165
220	198	242
320	288	352
460	414	506
680	612	748
1000	900	1100
1500	1350	1650

Table 4. AGMA viscosity grades for gear oils[4]

AGMA number	ISO grade equivalent	Kinematic viscosity at 40 ˚C, minimum cSt	Kinematic viscosity at 40 ˚C, maximum cSt	Kinematic viscosity at 100 ˚C, minimum cSt	Kinematic viscosity at 100 ˚C, maximum cSt
0, 0S	32	28.8	35.2	-	-
1, 1S	46	41.4	50.6	-	-
2, 2EP, 2S	68	61.2	74.8	-	-
3, 3EP, 3S	100	90	110	-	-
4, 4EP, 4S	150	135	165	-	-
5, 5EP, 5S	220	198	242	-	-
6, 6EP, 6S	320	288	352	-	-
7, 7 Comp, 7EP, 7S	460	141	506	-	-
8, 8 Comp, 8EP, 8S	680	612	748	-	-
8A Comp, 8A EP	1000	900	1100	-	-
9, 9EP, 9S	1500	1350	1650	-	-
10, 10EP, 10S	-	2880	3520	-	-
11, 11EP, 11S	-	1440	5060	-	-
12, 12EP, 12S	-	6120	7480	-	-
13, 13EP, 13S	-	-	-	190	220
14R	-	-	-	428.5	857.0
15R	-	-	-	857.0	1714.0

high viscosity lubricant could stay in place and act like a cushion in the contact area.

Containability

In some applications where a fluid lubricant would leak out, a grease might be recommended. However, it is still important to consider both the base fluid viscosity and the NLGI grade when selecting the proper lubricant. If the lubricant's viscosity or consistency is too high, it might not flow where it is needed and the lack of lubricant – a condition known as lubricant starvation – would lead to metal-to-metal contact. This would cause wear that could ultimately result in equipment failure. The same thing could happen with a lubricant with too low a viscosity or consistency, because it might not stay in the area where it is needed.

Viscosity classifications

Fortunately for the end user, various technical societies have created classifications that are used by lubricant manufacturers when formulating the proper viscosity grade of lubricant needed for equipment. These viscosity classification systems are commonly used to describe both industrial and automotive lubricants. These standardised viscosity ranges are used by lubricant formulators, original equipment manufacturers and lubricant consumers when labelling, marketing, specifying and using lubricants.

Fluid lubricant viscosity classifications

The Society of Automotive Engineers (SAE) has created two viscosity standards for automotive lubricants. SAE J300 is a viscosity classification for engine oils, and SAE J306 is for axle and manual transmission lubricants. The J300 viscosity grades and their requirements are summarised in Table 1, while those for J306 are shown in Table 2. In both of these classifications, the grades denoted with the letter 'W' (for 'winter grade'), are intended for use in applications operating in low temperature conditions, whereas the grades without a 'W' are recognised as monograde, or straight grade, lubricants.

Industrial fluids are also specified according to various viscosity classifications. ASTM International and the Society of Tribologists and Lubrication Engineers (STLE)

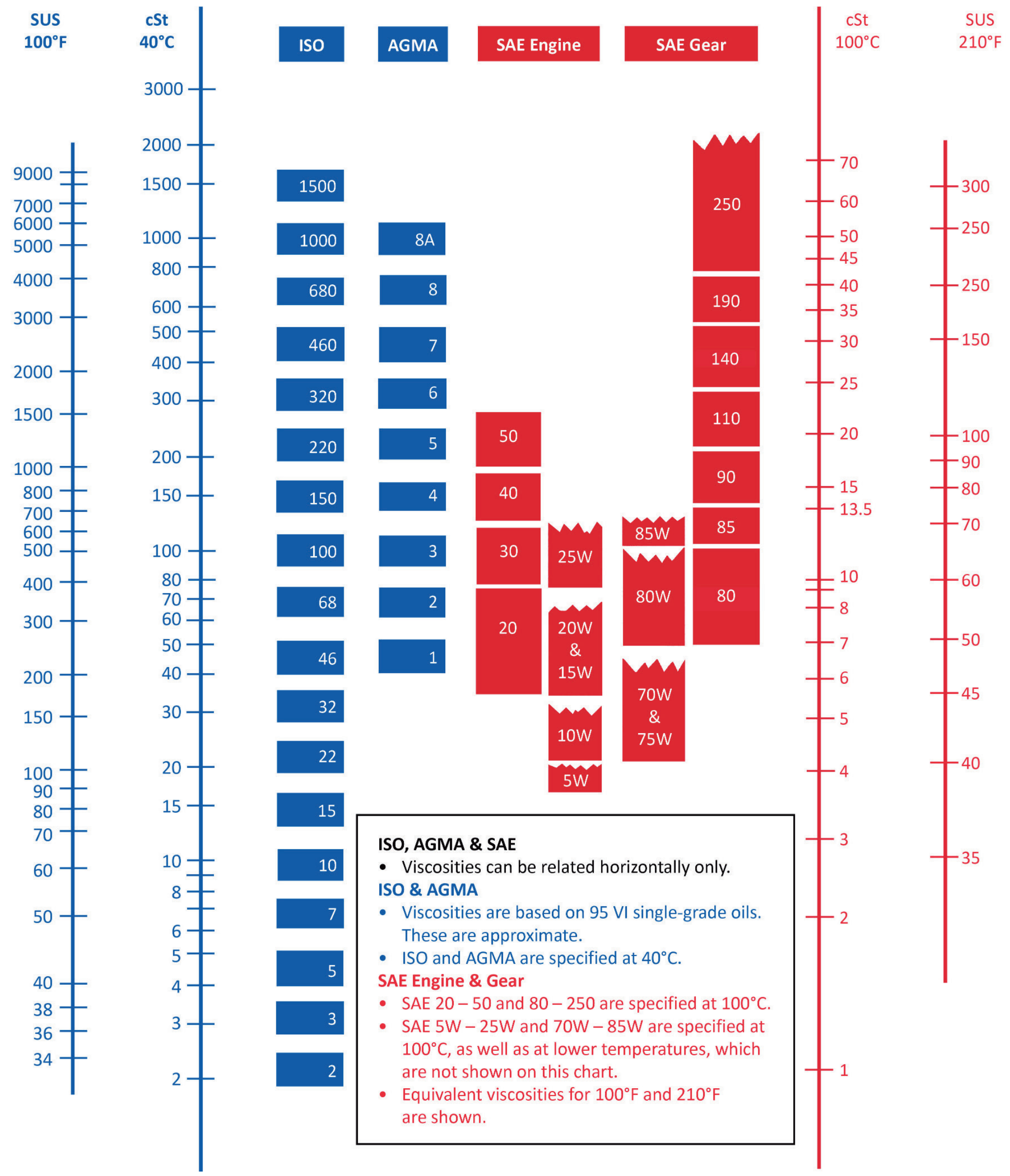

Figure 1. Viscosity equivalents.[5]

jointly developed the most frequently used industrial viscosity classification. It was recognised as ASTM D2422. This method originally standardised 18 different viscosity grades measured at 100 ˚F in Saybolt Universal Seconds (SUS). It was later converted to more universally accepted metric system values measured at 40 ˚C. The system eventually received international acceptance. These viscosity ranges are denoted in Table 3 and are usually recognised as 'ISO viscosity grade numbers', often shortened to 'ISO VG numbers'.

The American Gear Manufacturers Association (AGMA) has also created a commonly used viscosity classification system, which is partially based on the ISO VG system, noted in Table 4. The AGMA numbers let the user know the ISO viscosity grade and some basic information about the gear lubricant's chemistry. If the product is a mineral oil that contains only rust and oxidation (R&O) additives, it will be recognised with only the AGMA number. If it is a mineral oil with extreme pressure additives, it is recognised with the AGMA number followed by the 'EP' designation. AGMA numbers followed by an 'S' denote synthetic gear oils. Compounded gear oils contain 3 – 10% fatty or synthetic fatty oils and are noted by the AGMA number with 'Comp' after it. Some gear oils contain residual compounds called diluent solvents that are used to temporarily reduce the viscosity, making it easier to apply. In this case, the AGMA number is followed by an 'R', which describes the product prior to the addition of a diluents solvent.

For clarity, a viscosity equivalent chart (Figure 1), provides a comparative illustration of all of the grades shown in Tables 1 through 4. For example, the chart indicates that an SAE 50 engine oil and an SAE 90 gear oil are the same viscosity.

As with anything, viscosity classifications have changed over time. As mentioned previously, viscosity used to be commonly recorded in SUS units in the US. As the economy has become more global, different standards organisations have worked together to standardise units of measure, including viscosity units. Some older equipment is still in operation that specifies the lubricant viscosity in the older units. The OEM might designate it with SUS units, while end users might refer to it in 'seconds'. Fortunately, there are common conversions that can be used to estimate the cSt value from the SUS value.

Brief descriptions of viscosity tests

Low temperature viscosity of automotive fluid lubricants measured by a Brookfield viscometer

The low temperature, low shear rate viscosity of gear oils, automatic transmission fluids, torque and tractor fluids, and industrial and automotive hydraulic oils is often specified as Brookfield viscosity. This test method introduces the fluid lubricant into a cooled bath for 16 h, and then uses the Brookfield viscometer for the determination of its low shear rate viscosity in the temperature range from -5 to -40 °C, and in the viscosity range of 1000 to 1 million cP. The result is reported in cP at a given temperature.[6]

Kinematic viscosity of transparent and opaque liquids

In this method, the time for a fixed volume of liquid lubricant, either transparent or opaque, to flow under gravity through a calibrated capillary viscometer at a given temperature (usually 100 ˚C and 40 ˚C) is measured. The kinematic viscosity is then calculated by multiplying the measured flow time by the calibration constant for that viscometer. The viscosity is then reported in cSt at a given temperature.[7]

Calculating viscosity index from kinematic viscosity at 40 ˚C and 100 ˚C

The viscosity index (VI) is an arbitrary measure of the variation in the kinematic viscosity of a petroleum product due to changes in temperature between 40 ˚C and 100 ˚C. For example, a higher VI indicates that the kinematic viscosity of the lubricant will decrease very little when the temperature is increased (Figure 2). The VI is simply reported as a numerical value that has no units.[8]

Measuring viscosity at high shear rate and high temperature by tapered bearing simulator

Viscosity at the shear rate and temperature of this test method is thought to be representative of the condition encountered in the bearings of automotive engines in severe service. In this method, the viscosity of fluid is measured using a tapered bearing simulator-viscometer. This viscometer uses a closely fitted rotor inside a matched stator to subject the fluid to a 1 x 10^6 s^{-1} shear rate at 150 ˚C. The rotor exhibits a reactive torque response when it encounters resistance from oil that fills the area between the rotor and the stator. This torque is measured and compared to calibration oils with known torque values to determine the viscosity of the test oil. The resulting viscosity is then reported in cP units.[9]

Determination of yield stress and apparent viscosity of engine oils at low temperature

When a fluid is cooled, the rate and duration of cooling may affect the oil's yield stress and viscosity. In this test method, oil is cooled slowly through a temperature range in which wax crystallisation is known to occur, followed by rapid cooling to the final test temperature. Correlations have been found between lack of pumpability in real field applications and failures in this test. These failures in the field are thought to be the result of the oil forming a gel structure that results in excessive yield stress or viscosity of the engine oil, or both. In this test, test fluid is placed in the cells of the Mini Rotary Viscometer (MRV), held at 80 ˚C for a short time, then cooled at a programmed cooling rate over a period exceeding 45 h to a final test temperature between 15 ˚C and 35 ˚C. A low torque is applied to a rotor shaft to measure the yield stress. A higher torque is then applied to determine the apparent viscosity of the sample oil. The low temperature viscosity is reported in the standard unit of millipascal-second (mPa-s), but may also be reported in cP units, which are numerically equal to mPa-s.[10]

Apparent viscosity of engine oils between -5 ˚C and -30 ˚C using the cold-cranking simulator

The apparent viscosity of automotive oils at low temperatures is measured using the cold-cranking simulator (CCS). As the name would suggest, results from this test have been correlated with low temperature engine cranking field data. In this test method, an electric motor drives a rotor that is closely fitted inside a stator. The space between the rotor and the stator is filled with oil. The test temperature, in the range of -5 ˚C to -30 ˚C, is measured near the stator inner wall and maintained by a regulated flow of refrigerated coolant through the stator. The speed of the rotor is calibrated as a function of viscosity, and the test oil viscosity is determined from this calibration and the measured rotor speed. Shear stresses, shear rates and viscosity ranges are in the range of 50 000 to 100 000 Pa, 10^5 to 10^{-4} s^{-1}, and 500 to 10 000 mPa-s, respectively. The resulting viscosity is reported in mPa-s or cP units.[11]

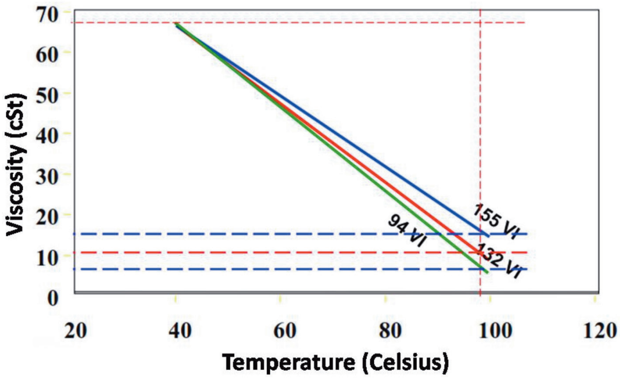

Figure 2. ASTM D2270 (calculation of viscosity index), measures the variation in kinematic viscosity of a petroleum product due to changes in temperature between 40 °C and 100 °C.

Figure 3. ASTM D217 (cone penetration test) evaluates the consistency of greases over the full range of NLGI numbers from 000 to 6.

Recent trends

Fluid lubricants

Considering its large volume and importance to so many consumers, it is not surprising that the engine oil market drives many new trends that occur within the lubricant industry. Today, articles are being written discussing the possible demise of monograde engine oils.[12] A number of years ago, straight grade engine oils, especially SAE 30 and SAE 40, were the most prevalent viscosity grades used by consumers. SAE is considering adding either two or three new viscosity grades to the SAE J300 Viscosity Classification.[13] The reason all of this is occurring is because much attention is being paid to improving fuel economy and energy efficiency. Governments are pushing automotive and industrial OEMs to find ways to improve the efficiencies of the vehicles and equipment produced, and lubricants have been considered as a means to decrease fuel and energy consumption. As viscosity is a measurement of the internal resistance of a fluid to flow, if the viscosity is decreased, then so is the internal resistance. Therefore, attention is now being paid to decreasing the viscosity of various lubricants to reduce their detraction from efficiency. Improved efficiency results in less energy consumed, which results in lower emissions released into the environment.

Due to the improvement seen through the use of multigrade engine oils, some studies have now been carried out that suggest that the same energy savings can be realised through the use of multigrade or synthetic industrial lubricants.[14] The majority of the work has been carried out in hydraulic fluids, which, not surprisingly, is the second largest category of lubricants by volume.

Used oils

One other area of interest is the viscosity of used oils. Analysing used oils is not new, but analysing them under high and low temperature operating conditions is. How will the effects of oxidation, contamination and shear affect the performance properties of the lubricant? A working group at ASTM has been formed, and it is planning a symposium to be held in the future to present research related to rheology (viscosity) of in-service lubricants.

Conclusion

If the wrong lubricant viscosity is selected for an application, the chances for equipment failure are dramatically increased. Therefore, the best rule is to always check the original equipment manufacturer's manual for lubricant viscosity recommendations.

If the OEM makes no recommendations, then the next step is to consider the operating speed, temperature and load of the application to be lubricated. Finally, after making a lubricating product selection, it is important to closely monitor the equipment to ensure the right choice was made. If possible, visually observe the moving parts to verify that a sufficient lubricant film is present to protect them. If not, listen for any unusual load grinding, chattering or squalling noises, which are often indications of metal-to-metal contact. Finally, one last technique is to contact lubricant manufacturers for recommendations. They can often provide technical support for proper fluid or grease selection.

Simply put, viscosity is probably the most important property of a lubricant, and a correct lubricant selection will better ensure long life expectancy of equipment and efficiency.

> If the wrong lubricant viscosity is selected for an application, the chances for equipment failure are dramatically increased. Therefore, the best rule is to always check the original equipment manufacturer's manual...

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