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ZPlus™ Tech Brief #13

Oil Viscosity

When people hear the word "*viscosity,*" they think of the thickness of a liquid: the higher the viscosity the thicker the liquid, the lower the viscosity the thinner the liquid. While this definition also applies to oil, the system used to label the viscosity of Passenger Car Engine Oil (PCEO) is one of the least understood automotive specifications. The dual-numbering system (i.e., 10W-30) used with multi-viscosity oils has further clouded most people's understanding of viscosity. It is important to have a good understanding of viscosity, for viscosity is the single most important characteristic of oil as a good lubricant. Our intent is to present some facts about the nature of viscosity in a way that will help clear up this important specification, leading to better informed choices when choosing a specific viscosity oil for your engine.

What Causes Viscosity?

Viscosity is a property of a liquid related to its state transition temperatures. This sounds complex, but it is not. Let's first review the different forms or states that any substance like oil can take. At any temperature and pressure, most substances can exist in one of three states: solid, liquid, or gas. The state a substance takes depends on its temperature and the pressure to which it is being subjected.

At an atomic level, the two main forces at work that determine whether a substance is solid, liquid, or gas are: the kinetic (heat) energy of the atoms, and the attraction between the atoms.

The relationship between applied energy and the state of a substance is graphically presented in figure 1.

Atoms rapidly move around at random, and in doing so establish a space around themselves which is proportional to their kinetic energy. This means the hotter a substance is, the greater the space each atom occupies. This is the reason why solids expand with an increase in temperature, a characteristic called the *coefficient of expansion with temperature*.

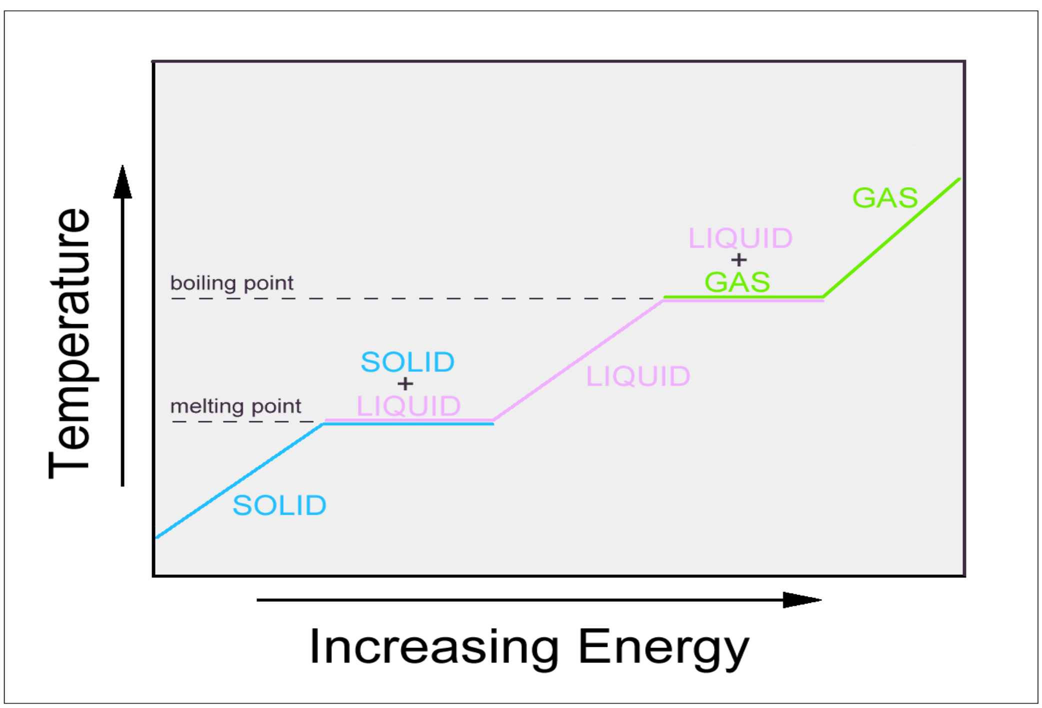

figure 1 - Temperature Increase with Applied Energy

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Atoms have an attraction to other atoms which varies with distance: the farther apart the atoms are, the more loosely held together the substance becomes. When a substance is in a solid state, the atoms do not have enough energy to escape the mutual attraction between them, so they condense into a tightly packed matrix with the atoms strongly held in a fixed relationship to each other.

If the temperature of that solid raises to the melting point, atoms acquire enough energy to break the electronic attraction and become mobile. This is the liquid state where the atoms may be freed from a fixed relationship, but they are still attracted to each other enough to stay in close proximity.

If a liquid is heated even further, its atoms or molecules will eventually acquire enough kinetic energy to separate from each other and become liberated from the electronic attraction. This is called the *gaseous* state where atoms have attained enough energy and velocity to totally escape the mutual attraction, and they will spread out and dissipate if given the room to do so. Oil is a complex substance with each hydrocarbon molecule consisting of many atoms of carbon, hydrogen, oxygen and others. The atoms in each hydrocarbon molecule are strongly chemically bonded together, and the energy required to break a hydrocarbon molecule apart is much higher than the energy needed to change it from a liquid state to a gaseous state. This property allows us to use vapor distillation to separate the various components of crude oil in the refining process.

There are other states of matter like supercritical fluids and plasmas, but we will not need to discuss them in this Tech Brief.

The basic property which gives liquid the characteristic we perceive as viscosity is *cohesion*. Cohesion is an expression of how strongly molecules of a substance are attracted to other molecules of that same substance. This in turn is partly dependent on the size (or weight) of each molecule. It is easy to imagine that a liquid made up of long, stringy molecules would be more viscous than one composed of shorter molecules. It is for this reason increasing viscosity oils are usually more dense as well.

We all know that the temperature can determine whether a substance is solid or liquid, but why does the viscosity of a liquid like oil change with temperature? This is due to the nature of liquids: they are substances where the molecules are loosely associated with one another. The thermal energy of liquid molecules makes them move around rapidly and maintain a large distance from other molecules, as compared to a solid. As the molecules gain energy, they are free to increase their distance from each other, causing the liquid to flow more easily. This brings us to the definition of viscosity:

Viscosity (noun)

Main Entry: **vis·cos·i·ty**
Pronunciation: \vis-'kä-sə-tē\
Function: *noun*
Inflected Form(s): plural vis·cos·i·ties
Etymology: Middle English *viscosite*, from Anglo-French *viscosité*, from Medieval Latin *viscositat-, viscositas*, from Late Latin *viscosus viscous*
Date: 14th century

1: the quality or state of being **viscous**
2: the property of resistance to flow in a fluid or semifluid
3: the ratio of the tangential frictional force per unit area to the velocity gradient perpendicular to the direction of flow of a liquid —called also coefficient of viscosity

figure 2 - Webster's Definition of Viscosity[1]

A key to understanding why viscosity is critical to lubrication is in the second definition: "...resistance to flow...". If a lubricating oil had zero resistance to flow, it would not stay in the gap of a bearing under load, and would immediately flow away from the point of loading. It is the viscosity property of oil which keeps it in a film, allowing it to lubricate and separate surfaces that may otherwise rub or contact each other.

[1] Merriam-Webster's Online Dictionary: http://www.merriam-webster.com/dictionary

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The oil film also offers resistance to flow due to its adhesion to the surfaces of the bearing. Oil which is dripping or running down a surface by gravity or is being pumped through a pipe shows resistance to flow due to its adhesion to the surfaces as well as its viscosity. In the case of a spinning bearing journal, the oil adhered to the bearing insert is stationary, and the oil adhered to the journal is moving at the speed of the journal. The oil layer adhered to the stationary surface is itself stationary, whereas the oil layers farther away from the surface move progressively faster. This velocity gradient forces the oil molecules to slide by each other against their mutual cohesion, a process called *shear*. Shearing oil causes heating of the oil and uses energy. This is one reason why many modern fuel-efficient engines specify low-viscosity oil. The lower the viscosity, the less energy it takes to shear the oil and the cooler the oil, but conversely, the lower the viscosity, the thinner the oil film. This is the basic challenge engineers face when designing engine lubrication.

For a more in-depth explanation of shear and lubrication, please read ZPlus™ Tech Brief #11 - Internal Combustion Engine Lubrication.[2]

Those familiar with physics will recognize the three-state diagram in figure 3. It shows the relationship between the two main factors which determine what state a substances will take. Although the state diagram is most directly applicable to pure substances, it is a useful tool to help understand factors that affect viscosity.

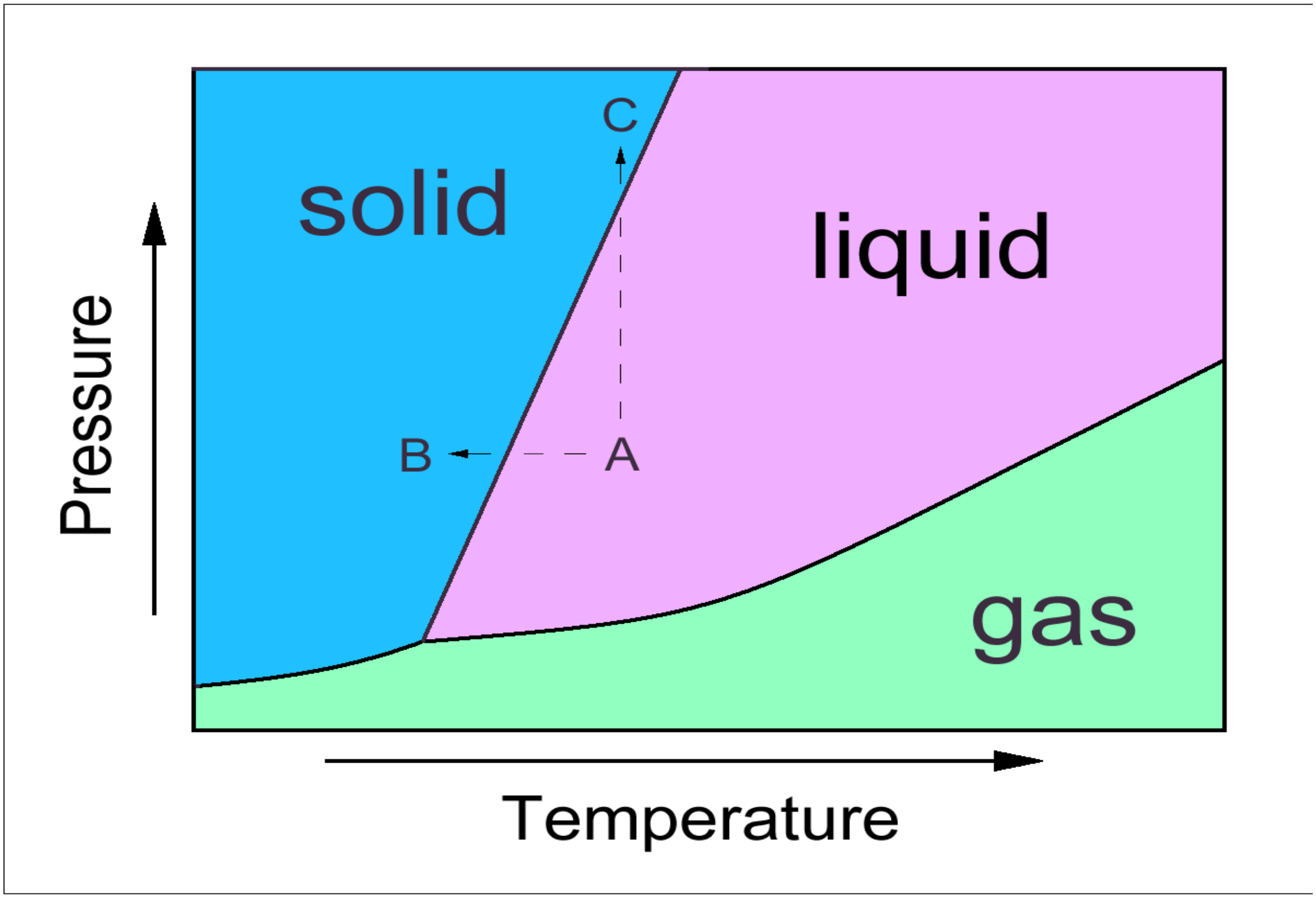

figure 3 - State Diagram

PCEO is a mix of different liquid oil molecules. When different oils are combined, the state diagram for the composite oil has regions of state transition instead of well defined state transition points. In other words, the transitions occur over a range of temperatures and pressures, not one well defined point. Nevertheless, from the state diagram in figure 3, we can see that as an oil is cooled from a liquid at point “A,” it will transition to a solid at some point near “B.” For mineral PCEO this is related to the *Cloud Point*, where the heaviest waxy fractions begin to solidify in suspension, and the *Pour Point*, where the oil becomes too thick to pour. An oil does not transition from a thin liquid to a solid at a single temperature, instead it has a viscosity increase which is proportional to temperature decrease.

[2] Hoyt, H., *ZPlus™ Tech Brief #11 - Internal Combustion Engine Lubrication*, ZPlus™, LLC, 2609 Tucker St, Burlington, NC, 27215, 2009, http://www.zddplus.com/TechBrief11 - Internal Combustion Engine Lubrication.pdf

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This relationship is well understood and quantified for mineral oils.

Another characteristic of oils graphically illustrated in figure 3 is the *Viscosity / Pressure ('α')* characteristic. If an oil at a fixed temperature is compressed from a liquid at point "A," at some high pressure its molecules will become close enough to form a solid structure at point "C." This characteristic of some oils is used to advantage when lubricating in the Elasto-Hydrodynamic (EHD) regime. Under these conditions, greatly thickened or solidified oil can transfer high loads without flowing away from the pressure point, which would allow metal-to-metal contact.

So pressure and temperature determine the viscosity of a single oil molecule type, but consider that a single-weight mineral oil is a mixture of tens of different oil molecule types, each with a different viscosity! In this case, what we measure as viscosity is the bulk average viscosity of the mixture. This will be a value somewhere between the highest and lowest viscosity oil type in the mixture.

Taking these factors into account, you can appreciate that there are many combinations of different oil types which can result in an oil of the same viscosity. If you were to submit two of these hypothetical oils to a suite of SAE standard viscosity tests, you could conceivably obtain the same SAE grade rating from two totally different oil types, yet they could show characteristics which varied widely with temperature extremes and other environmental factors. This is the reason why differing oils of the same viscosity rating can show such different characteristics in use. It is also one reason why a true synthetic composed of Group IV or V base stocks can have better defined characteristics: they are typically made with a synthetic oil of a narrow range of molecular types with a much narrower range of characteristics.

For a more thorough discussion of the different types of base oils, please refer to ZPlus™ Tech Brief #10 - Oil Base Stocks.[3] This paper focuses on the viscosity characteristics exclusively.

Viscosity Measurement Methods

There are two most commonly used methods for testing and rating viscosity of oil:

Dynamic Viscosity is closely related to the "thickness" of an oil, and does not depend on the density of the sample. It is commonly expressed using the unit $kg \cdot m^{-1} \cdot s^{-1}$, or milliPascal seconds (mPa*s), also called centiPoise (cP). Water at 68°F (20°C) has a viscosity of about 1.0 cP. A dynamic viscosity test uses a controlled, measured sliding or rotating force to shear the liquid under test.

Kinematic Viscosity test results are affected by the density of the oil, and often use the acceleration of gravity or vibration as forces to shear the oil under test. The unit of measurement is millimeters^2/second, also called centiStoke (cSt). Water has a density of 1 gram per cubic centimeter, and at 68°F (20°C) it has a viscosity of about 1.0 cSt.

The two different methods of testing and rating viscosity are examining the same viscosity characteristic of the liquid, but use a different applied force to move and shear the liquid, and differ only by the density of the liquid. Translation between the two measurement systems can easily be done by the following operations. [4]

Dynamic Viscosity (cP) / Density (g/mL) = Kinematic Viscosity (cSt)
Kinematic Viscosity (cSt) * Density (g/mL) = Dynamic Viscosity (cP)

One way to conceptualize the difference is to consider that the most common way to test kinematic viscosity has been the use of a timed orifice method, such as the Saybolt apparatus or Zahn cup. In the commonly used Zahn cup test, a cup with a calibrated hole in the bottom is filled to a reference line. The kinematic viscosity is determined by the time it takes for a known quantity of the liquid to run out of the hole. If a liquid of a similar measured dynamic viscosity but greater density is tested in the apparatus, it will show a lower kinematic viscosity, because its greater mass per unit volume pushes the liquid through the orifice at a greater rate.

Another viscosity rating system, somewhat obsolete but still found in some oil specifications and used by people who work with older vehicles, is the Saybolt Universal Second (SUS). This system is a kinematic viscosity rating, and 1.0 SUS = 0.2158 cSt.

The viscosity comparison between water and mercury in figure 4 illustrates the difference between dynamic and kinematic viscosity measurements. At 77°F (25°C) water has a density of 1 g/ml and mercury has a density of 13.6 g/ml.

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[3] Hoyt, H., *ZPlus™ Tech Brief #10 - Oil Base Stocks*, ZPlus™, LLC, 2609 Tucker St, Burlington, NC, 27215, 2009, http://www.zddplus.com/TechBrief10 - Oil Base Stocks.pdf

[4] It is important when converting from the two viscosity measurement systems to use viscosity and density specifications at the same temperature.

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The dynamic viscosity measurement of water is 0.6 that of mercury in a rotating dynamic viscosity test, but water measures eight times as viscous as mercury in a kinematic gravity accelerated test using a cup. The difference is kinematic viscosity uses the force of gravity to accelerate the mercury for testing, and mercury's density (13 times greater than water) gives it greater mass which is pulled by gravity with more force. This makes it flow through the orifice much more quickly, which means its kinematic viscosity measures lower.

For most people, these two numbering systems do not convey a feel for the actual viscosity of a substance. In order to give a better feel for the numbers we will discuss in the SAE test section, figure 4 gives some viscosity ratings for common substances at two temperatures with both the dynamic and equivalent kinematic viscosities stated.

	77°F (25°C)			212°F (100°C)		
Substance	Density (g/ml)	Dynamic Viscosity (cP)	Kinematic Viscosity (cSt)	Density (g/ml)	Dynamic Viscosity (cP)	Kinematic Viscosity (cSt)
Water	1.0	0.89	0.89	0.96	0.28	0.29
30 Weight Oil	0.87	110	126	.83	8.3	10
Honey	1.38	5000	3570	1.0	40	40
Mercury	13.60	1.53	0.113	13.36	1.25	0.094

figure 4 - Relative Viscosities of Common Liquids

Viscosity Rating Systems

The SAE viscosity rating system for PCEO, as defined by the ASTM J300[5] specification, has two sections. Figure 5 shows the testing criteria which an oil must pass to obtain a low-temperature "W" viscosity rating. Figure 6 shows the high-temperature viscosity test criteria. In order to obtain a multi-viscosity SAE rating, an oil must pass the tests in both categories. In order to obtain an SAE multi-viscosity grade rating, an oil must be subjected to both sets of tests.

SAE Viscosity Grade	Low-Temperature Cranking Viscosity (cP)	Low-Temperature Pumping Viscosity (cP)	Low Shear-Rate Kinematic Viscosity Minimum (cSt)
0W	6200 at -31°F (-35°C)	60,000 at -40°F (-40°C)	3.8 at 212°F (100°C)
5W	6600 at -20°F (-30°C)	60,000 at -31°F (-35°C)	3.8 at 212°F (100°C)
10W	7000 at -13°F (-25°C)	60,000 at -20°F (-30°C)	4.1 at 212°F (100°C)
15W	7000 at -4°F (-20°C)	60,000 at -13°F (-25°C)	5.6 at 212°F (100°C)
20W	9500 at 5°F (-15°C)	60,000 at -4°F (-20°C)	5.6 at 212°F (100°C)
25W	13,000 at 14°F (-10°C)	60,000 at 5°F (-15°C)	9.3 at 212°F (100°C)

figure 5 - SAE "W" Viscosity Determination Chart

Referring to figure 5, you will see the first number of the viscosity rating of a multi-viscosity oil ("W" number) which is defined by three separate tests. The first test, Low Shear-Rate Kinematic Viscosity, determines a minimum 212°F (100°C) viscosity. The oil's viscosity is then evaluated at much lower temperatures using two other tests to determine the cranking and pumping characteristics. The SAE Viscosity Grade determined using these tests is designed to report an oil's cold weather performance.

Low-Temperature Cranking Viscosity testing is performed using the procedure described in ASTM D5293.[6] In this test, a Cold-Cranking Simulator (CCS) is employed, consisting of a close fitting rotor and stator at a controlled temperature. The oil under test is placed in the gap between the two, and the amount of motor current necessary to keep the rotor at a reference speed is recorded. The thicker the oil, the greater the viscous drag between the rotor and stator, so this current will equate to a specific viscosity. The temperature is lowered and the test repeated until the viscosity exceeds that allowable for the grade. The lowest temperature test passed by the oil determines the SAE "W" Viscosity Grade of the oil.

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[5] SAE Standard J300, *Engine Oil Viscosity Classification*, SAE International, 400 Commonwealth Dr., Warrendale, PA 15096, Jan 2009.

[6] ASTM Standard D5293-08, 2008, *Standard Test Method for Apparent Viscosity of Engine Oils and Base Stocks Between -5 and -35°C Using Cold-Cranking Simulator,* ASTM International, West Conshohocken, PA, 2003, www.astm.org .

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In order to pass the SAE requirements for the grade determined using the CCS test, the oil must also pass a Low-Temperature Pumping Viscosity test, performed according to ASTM procedure D4684.[7] This test determines the temperature at which the oil reaches 60,000 cP viscosity, as well as watching for any sign of *Yield Stress*. Yield Stress in oil is an indication the oil is beginning to gel or solidify. When this occurs, a low and constant force will not move the oil as it would liquid oil. No yield stress is permissible in an oil in order to pass the Low-Temperature Pumping Viscosity test.

Referring to figure 6, the normal viscosity (which is also the second number in a multi-viscosity oil designation) is determined by performing two tests. As with the low-temperature designation, the first test is a Low Shear-Rate Kinematic Viscosity determination to obtain the reference 212°F (100°C) viscosity. Each SAE grade has a range of kinematic viscosities which determine the SAE grade. Particularly in the 20-weight grade, there can be as much as a 60% difference between two oils, each of which are classified as SAE 20-weight.

SAE Viscosity Grade	Low Shear-Rate Kinematic Viscosity Range (cSt)	Viscosity Range in Grade (%)	High Shear-Rate Viscosity Minimum (HTHS) (cP)
20	5.6 to <9.3 at 212°F (100°C)	60	2.6 at 302°F (150°C)
30	9.3 to <12.5 at 212°F (100°C)	34	2.9 at 302°F (150°C)
40	12.5 to <16.3 at 212°F (100°C)	30	3.5 (0,5,10W-40) at 302°F (150°C)
40	12.5 to <16.3 at 212°F (100°C)	30	3.7 (15,20,25-40) at 302°F (150°C)
50	16.3 to <21.9 at 212°F (100°C)	34	3.7 at 302°F (150°C)
60	21.9 to <26.1 at 212°F (100°C)	20	3.7 at 302°F (150°C)

figure 6 - SAE Standard Viscosity Determination Chart

The oil is then subjected to a High-Temperature High Shear (HTHS) test at 302°F (150°C) following ASTM procedure D4683,[8] to determine how the oil film stands up to more severe high-temperature conditions with the film under high shear. The oil must pass the minimum rating in order to actually qualify for the SAE rating. This second test is intended to determine high-temperature and high shear performance, which is relevant to the lubricating quality of an oil for rings and bearings.

An oil's characteristics (such as flash point, pour point and general viscosity) are design factors at the time of the original formulation by the manufacturer. As you now know, the SAE viscosity designation printed on the bottle is instead arrived at by testing *after* formulation to the SAE test criteria. Most people equate the labeled SAE viscosity on a bottle of oil with the exact viscosity characteristics of the oil contained in the bottle. The truth is two different oils may have the same labeled SAE viscosity rating, yet have very different viscosity characteristics, especially at temperature extremes.

Multi-Viscosity Oil

The label *Multi-Viscosity* is somewhat of a misnomer. It implies the oil has the characteristics of two different oils, or contains two different oils. As you saw in the previous section on SAE ratings, it merely indicates the oil was subjected to two different sets of tests which result in two different numbers for the same oil. The term multi-viscosity is most commonly used to refer to oils which have been given a two-number API viscosity rating, such as 10W-30. In this context, the term multi-viscosity merely refers to the fact that the oil was tested under API guidelines at low and high temperatures, and states the reading attained in each test. In the case of some synthetic oils, this rating can often be achieved by an oil consisting of a single molecular type, without a Viscosity Index (VI) Improver. Multi-viscosity does not directly indicate an oil is a mix of oils of differing viscosities, nor does it mean an oil has a VI Improver added (although usually both are true).

Viscosity at Temperature Extremes

Oil manufacturer's specifications usually give a nominal 212°F (100°C) viscosity as well as 104°F (40°C), and these two ratings determine what SAE grade is assigned. Some manufacturers also provide the 302°F (150°C) HTHS viscosity

[7] ASTM Standard D4684-08, 2008, *Standard Test Method for Determination of Yield Stress and Apparent Viscosity of Engine Oils at Low Temperature*, ASTM International, West Conshohocken, PA, 2003, www.astm.org .

[8] D4683-04, 2004, *Standard Test Method for Measuring Viscosity at High Shear Rate and High Temperature by Tapered Bearing Simulator*, ASTM International, West Conshohocken, PA, 2004, www.astm.org .

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rating which informs the consumer about the oil's behavior under high shear, high-temperature conditions, such as that found in piston rings or bearings at high rpms.

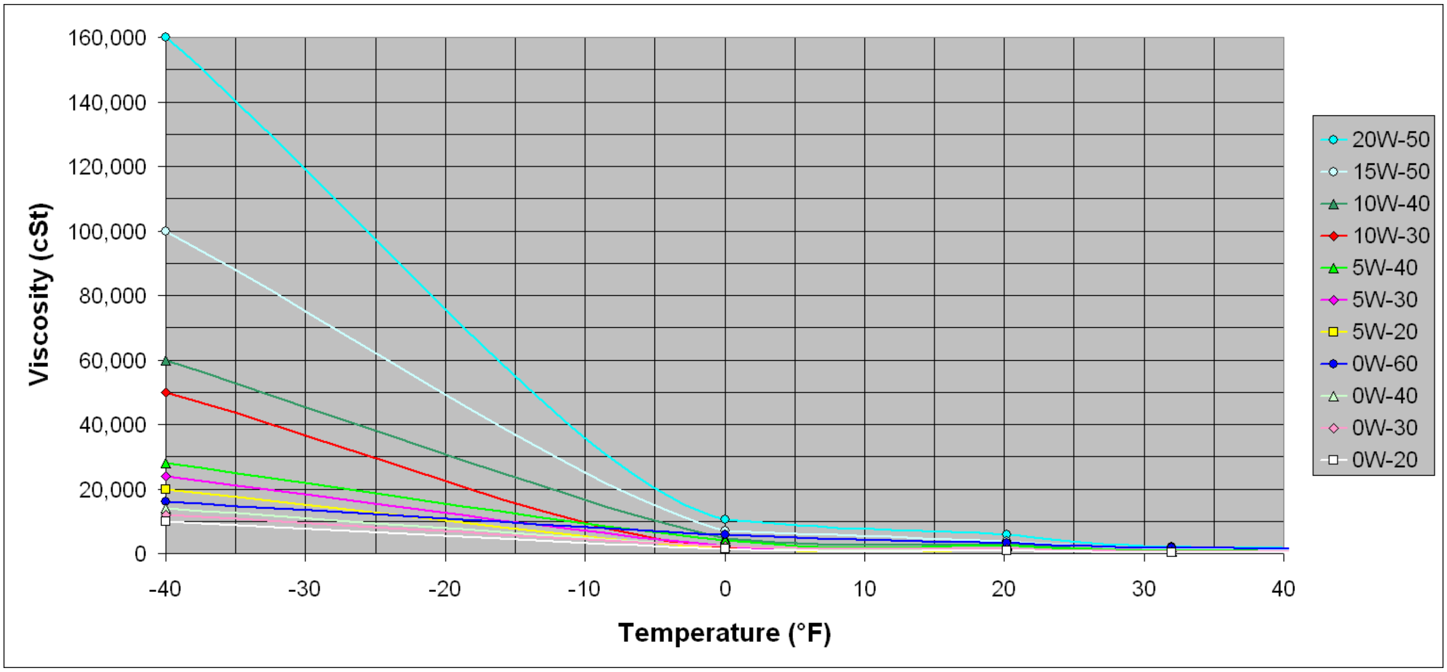

figure 7 - Low-Temperature Viscosity of Multi-Weight Oil

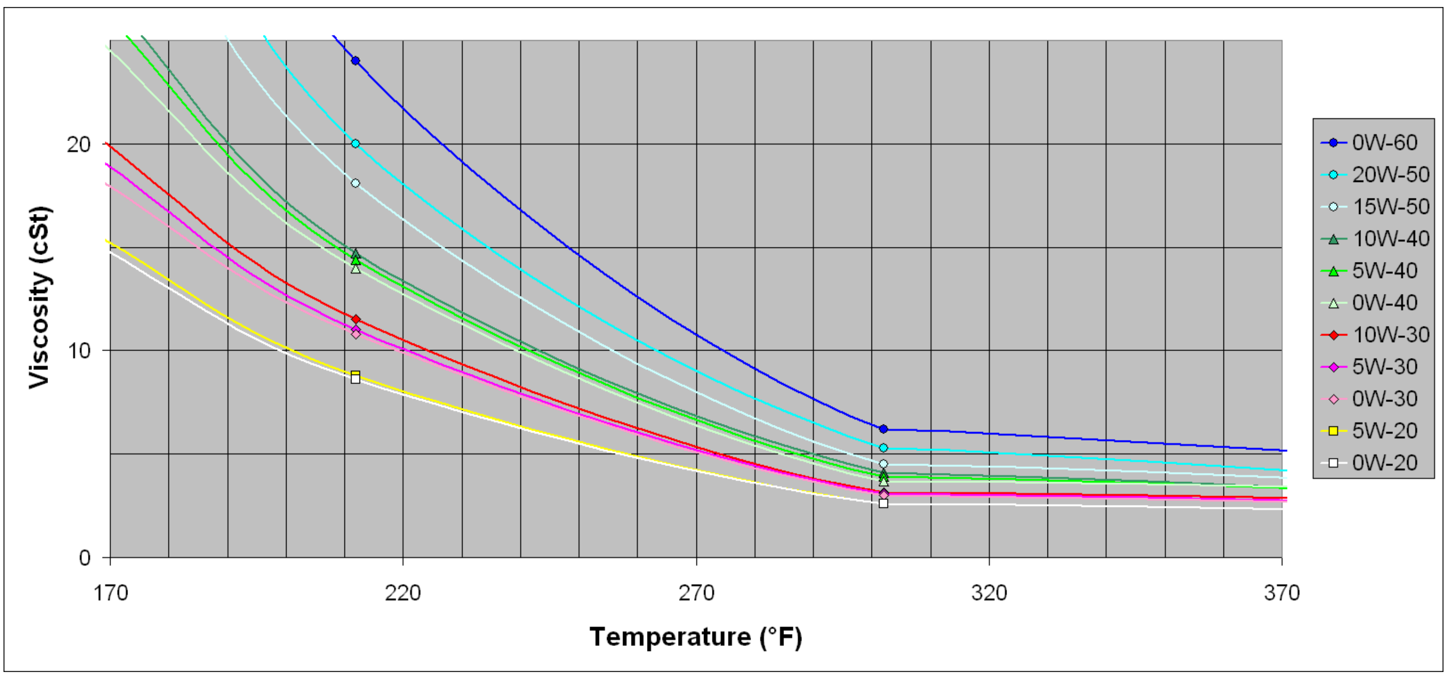

figure 8 - High-Temperature Viscosity of Multi-Weight Oil

The graphs in figures 7, 8, and 9 are based on averaged data from a range of commercially available oils, and do not represent any one oil. As shown in figure 6, the range of viscosities can be as great as 60% within a single SAE grade.

The graph at figure 7 shows the difference between oils of different cold ratings (W grade) at low temperatures. What is clear from this graph is that the first number in the multi-grade rating (the number followed by the W) is determined by the viscosity of the oil at the low temperature end of the range.

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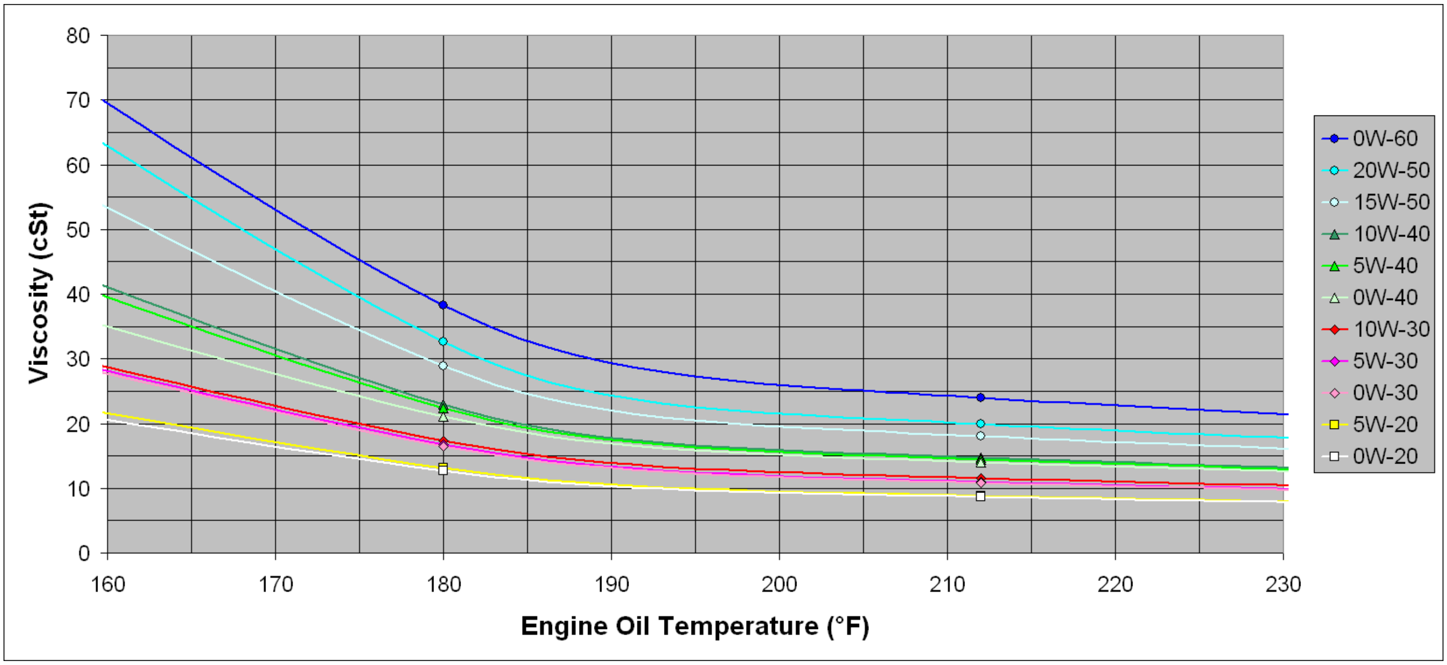

figure 9 - Engine Oil Temperature vs. Oil Viscosity for Different Multi-Viscosity Oils

While this seems obvious, many people fail to realize this when they consider the difference between 0W-30 and 10W-30 is merely the extreme low-temperature viscosity. At normal operating temperatures or high temperatures, the two can be virtually the same viscosity. As discussed in the VI Improver section of this paper on page 10, different oils can achieve similar viscosity vs. temperature characteristics in different ways.

Figure 8 shows the same oils at the high temperature extreme. The graph shows the high-temperature viscosity performance is closely related to the SAE standard grade (non-W grade) 212°F (100°C) rating. At any given standard viscosity, the oil with the highest VI will show the least thinning as the temperature increases.

Viscosity at Operating Temperature

Manufacturer's oil specifications usually give a nominal 212°F (100°C) viscosity as well as 104°F (40°C) viscosity. While the high- and low-temperature viscosity characteristics show important differences between the SAE grades, the most important specification is the design viscosity for your particular engine. By this we mean the viscosity specified by the manufacturer at the operating temperature of the engine. As the oil runs off of hot parts like pistons and is sheared by spinning bearings and sliding pistons, etc., the oil does indeed pick up a lot of heat. For most engines, the oil temperature under normal use will average between the thermostat temperature and 20° to 40°F above that temperature.

Referring to figure 9, you can clearly see the oil viscosity is highly dependent on temperature at the normal range of engine operating temperatures. If you choose the curve on figure 9 which represents the oil which your engine was specified to use, you can then see what the manufacturer's design viscosity is by finding the intersection of that curve and the normal oil temperature.

For example; if your engine came equipped with a 180°F (82°C) thermostat and was supplied with 10W-30 oil, then under normal loading the engine was designed to operate correctly with 17.3 cSt oil at 180°F (82°C) in the lubrication system. The only reason the manufacturer specifies different oils for different seasons is to ensure adequate oil flow at extremely low temperatures. Let's analyze the effects of changing your choice of viscosities.

If you decide to use 0W-20 oil to allow for easier cold weather starts, once the engine is warmed up the oil film thickness in the bearings will drop due to the 12.7 cSt viscosity of that oil, 27% lower than called for by the manufacturer. Depending on how close to design limits the bearings were operating, the oil film may not have sufficient thickness to keep the journal from rubbing on the bearing under load.

Conversely, if you switch to a 20W-50 oil in the belief it will give you better lubrication in hot or high-load conditions, you may not be getting the improvement you expect. This is because the additional viscosity will cause additional shear

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in the oil which results in shear heating and a viscosity reduction. Studies[9] show that a doubling of viscosity grade will cause as much as a 20°F (11°C) rise in oil temperature in the bearing under shear. If we assume a 20°F increase in oil bearing oil temperature when switching to 20W-50 oil, the viscosity in the bearing will drop as much as 30% in response to the temperature increase. Instead of the expected doubling of viscosity by using 20W-50 oil, the increase would be around 35%, with increased viscous drag and resulting power loss. The data obtained in the study was for industrial hydrodynamic bearings under a normal load, so the rise in temperature for a viscosity doubling may vary in an IC engine. Under heavy-duty conditions, the shear induced heating and viscosity reduction would be even more severe. Another possible long-term effect of the additional shearing with higher viscosity oil is irreversible thinning due to breakdown of the VI improver molecules.

One conclusion this study reached is to use the lowest viscosity consistent with adequate film thickness, which applies to internal combustion lubrication as well. To correctly decide what oil would satisfy these requirements, it would require a laboratory of expensive instrumentation. Fortunately, your engine's OEM has this equipment, and uses it to develop their recommendations.

Viscosity Index (VI)

All oils show a viscosity decrease with temperature increase, for the reasons presented previously. It is an inherent characteristic of liquids in general. The amount of viscosity loss proportional to temperature increase is called the Viscosity Index (VI), and it is a calculated value using the procedure in ASTM D2270.[10] Since engines are designed to operate correctly with oil of a specific viscosity value, it is advantageous to have an oil which loses viscosity as little as possible as the temperature increases. The less an oil thins as the temperature increases, the higher the VI. On the other end of the scale, it is an advantage to have oil that thickens as little as possible when the temperature drops. A high VI oil thickens less with a temperature decrease.

All 10-weight oils have a viscosity of approximately 4 cSt at 212°F (100°C), regardless of their VI. The difference between oils of different VI shows up at the temperature extremes. The graph in figure 10 shows the difference in the low-temperature viscosity of 10-weight oils of four different VIs between 75 and 150. The desirability of choosing an oil with a high VI is graphically illustrated. The oil with the VI of 75 is more than 3 times as viscous at -4°F, which could possibly make it much harder to crank and start an engine.

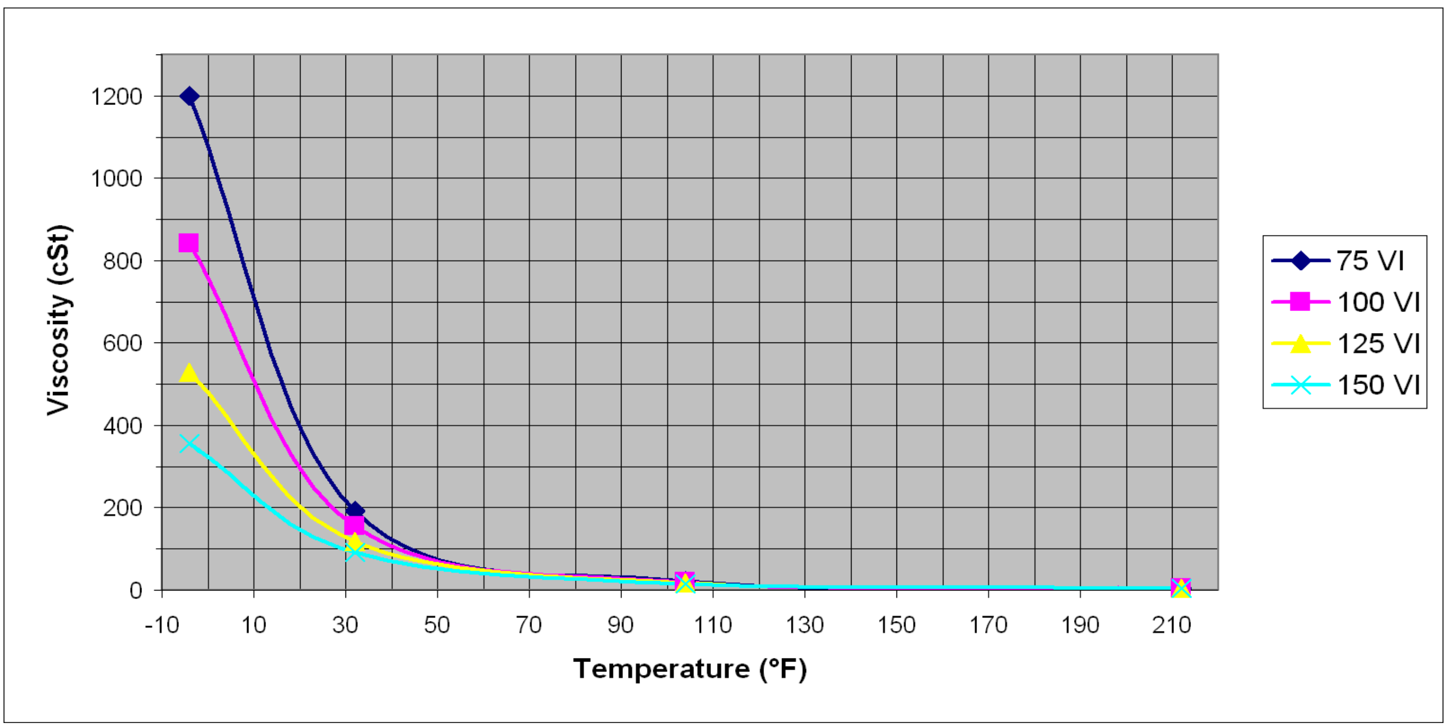

figure 10 - 10-Weight Viscosity Index vs. Low-Temperature Viscosity

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[9] Khonsari, M.M., Booser, E.R., *Cool Ideas for Sleeve Bearings*, Machine Design Magazine, Penton Media, Cleveland, OH., Vol. 81 No. 8, April 23, 2009.

[10] D2270-04, 2004, *Standard Practice for Calculating Viscosity Index from Kinematic Viscosity at 40°C and 100°C*, ASTM International, West Conshohocken, PA, 2004, www.astm.org .

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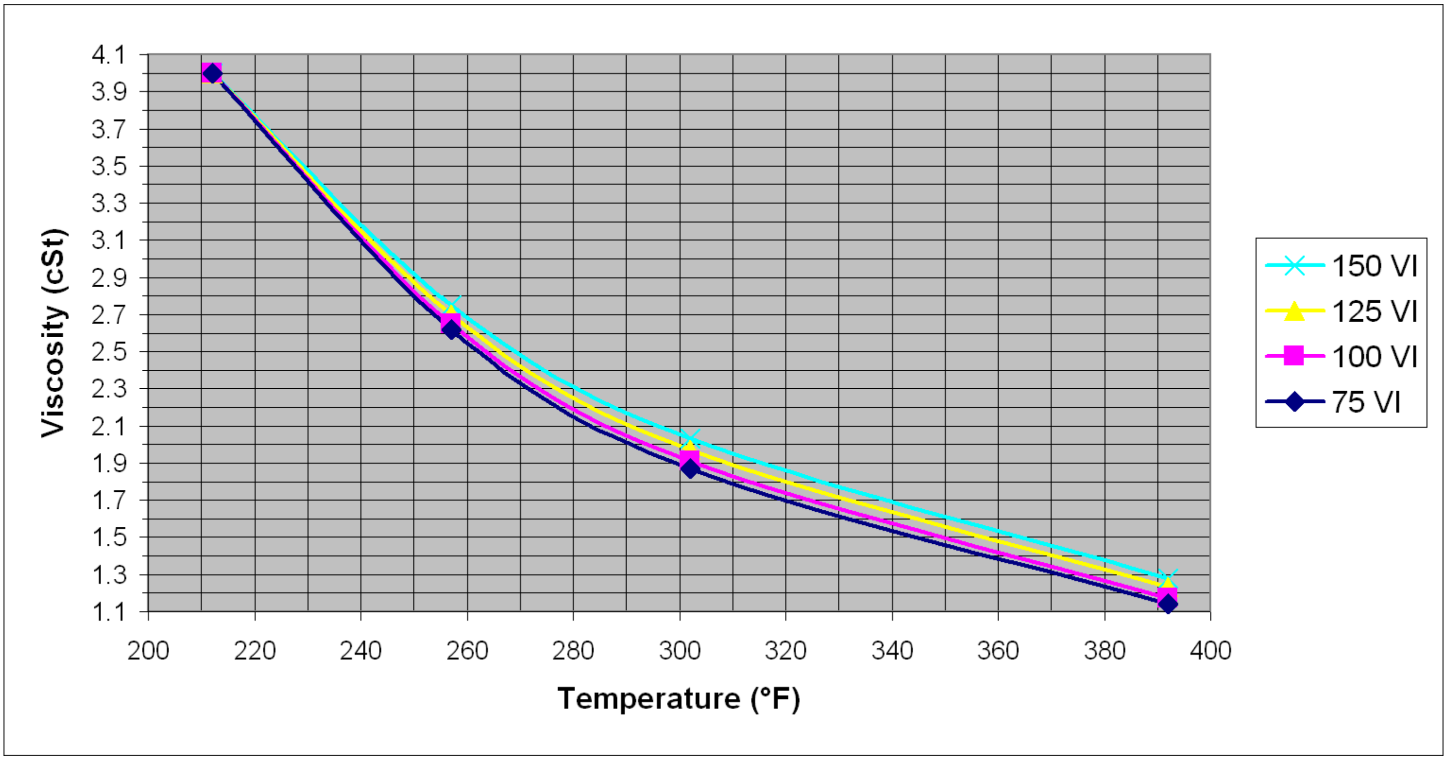

figure 11 - 10-Weight Viscosity Index vs. High-Temperature Viscosity

Figure 11 shows the difference between these same four 10-weight oils at high temperatures. The oil with the VI of 150 has a 20% higher viscosity at 392°F (200°C) than does the oil with the VI of 75, showing the superiority of a high VI oil at high temperatures as well.

Many modern oils have VIs higher than 150. In the case of some Very High Viscosity Index (VHVI) mineral oils, synthetics or synthetic blends, the VIs can be as high as 190. These oils will offer far better low-temperature starting and lubrication characteristics, as well as thicker lubricating films at high temperatures. If it were somehow possible to manufacture a 10-weight oil which did not change viscosity with temperature, it would have an equivalent VI of approximately 800. For practical reasons, it is unlikely that such an oil will be designed in the near future.

Not all manufacturers publish the VI. If you want to compare the VI of two oils with similar viscosity ratings, you can get a rough idea by subtracting the viscosity at 212°F (100°C) from the viscosity at 104°F (40°C) for each. The resulting number will not be an actual VI number, but the oil with the lower number will have the higher VI.

Viscosity Index (VI) Improvers

The relationship between temperature and viscosity for pure mineral oils is well known. A VI improver is typically a high-molecular weight polymer which has the desired characteristic of swelling in size as the temperature increases. This increase in molecular size increases the viscosity due to that polymer, which offsets the decrease in viscosity of the base oil. In this way, the Viscosity Index of oils can be increased by use of these polymers.

In general, VI improvers are not as stable as the base oils they are added to, and have less resistance to oxidation or degradation due to shear than does the base oil.[11] Therefore, between two oils with the same VI, the one with the lower amount of VI improver would be more thermally stable and suffer less viscosity loss, all else being equal.

The viscosity of base oils is not affected by the shear rate over a very wide range of rates. This characteristic makes oil a *Newtonian Fluid*. That is, its viscosity stays the same regardless of the amount of shearing. This is not true with polymer VI improvers, which are *non-Newtonian*. As shear is applied to them, they tend to display a drop in viscosity. This is a mixed blessing, since the drop in viscosity will mean less power is needed to shear the oil but of course, the oil film thickness will also drop. What this means is that two oils of the same apparent viscosity, but with different amounts of VI improvers to get that viscosity, will act differently under conditions of high shear. The oil with the least VI improver will

[11] Baillargeon, David J., et.al, High-Performance Engine Oil, Mobil Oil Corp., Patent Abstract # 6713438, pg.4, March 2004.

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retain its viscosity and film thickness better under conditions of high temperature and high shear.

The amount of viscosity loss under high shear conditions is called *shear thinning.* Oil companies closely guard their proprietary PCEO formulations, so unfortunately there is little way to tell the percentage of VI improvers in any specific oil. This leads to a guessing game as to which oil has the superior long-term performance under severe conditions. In reality, shear thinning is both a good and bad characteristic for engine oil. It can be good because a thinner oil takes less energy to shear which increases the economy of the engine, but bad because thinner oil establishes a thinner film. The High Temperature, High Shear (HTHS) test following ASTM D4683 is the rating which some manufacturers will present as proof of high shear performance. A rough estimate of shear thinning and possible VI improver content can be obtained by extrapolating the viscosity at 302°F (150°C) using the published 104°F (40°C) and 212°F (100°C) ratings. The published HTHS viscosity is then subtracted from the extrapolated 302°F (150°C) viscosity. The difference is the shear thinning value, and is due to VI improver viscosity loss in the HTHS test. Comparing the shear thinning value between two oils with otherwise similar viscosity ratings can provide a rough estimate of the relative VI improver content. The best oils which have an inherently high VI usually publish the HTHS value. Base oils with a low VI which require a large amount of VI improver may not publish the HTHS value, as the PCEO formulated in this way will show a larger drop in viscosity.

True synthetics (such as PAG or PAO) can have higher viscosity indexes than plain mineral oils without the addition of VI improvers. This being said, most fully-formulated synthetic PCEO do have VI improvers added to further increase the viscosity index.

Viscosity and Flow

There is a commonly held idea that some oils have superior “flow” than others of the same viscosity. Viscosity is a liquid’s resistance to flow, so by definition they are dependent and have an inverse relationship. Two oils with identical viscosity characteristics will show identical flow characteristics. This being said, as we saw in the SAE oil classification tables, there is as much as a 60% viscosity difference possible between one 20-weight oil and another. This means these oils with identical “SAE 20-weight” labeling but different viscosity will have a different flow characteristic as well.

Some manufacturers claim superior high-temperature flow for their oil, possibly due to shear thinning in conditions of HTHS. As we discussed, this is a mixed blessing and a potential pitfall, especially if the VI improver suffers irreversible viscosity breakdown in the process. In many light-duty passenger car applications, the action of the VI improver is desirable and reliable for the recommended oil change interval.

Conclusions on Picking Oil Viscosity

Most engine oil pumps are of the positive displacement gear type, and assuming the inlet is not starved, they will pump similar volumes of oil at any given rpm whether the oil is cold or hot. The amount of power required to pump this volume will vary proportionally with temperature. This means the pressurized bearings in the engine will still get oil even at the lowest pumpable temperature. Being cold the oil will be highly viscous, protecting the bearings from wear. The biggest risk with thick, cold oil near the minimum pumping temperature is insufficient ring lubrication, due to the oil being too viscous to splash onto or flow correctly on cold cylinder walls.

The primary factor to consider when choosing an oil is the manufacturer’s recommendations for the normal (non-W) viscosity and thermostat temperature. The combination of the two establishes an operating viscosity which is a critical design criterion for many engine systems. Changing the operating viscosity is not advisable! Of course, heavy-duty, Arctic or other operation not covered under the original design of the vehicle may dictate a different approach.

If your vehicle was designed to use a 10W-30 oil, the use of a 0W-30 oil will give similar oil viscosity at operating temperatures, but allow for superior lubrication on start and warm-up. Many older cars were made before the recent development of multi-viscosity oils with a 0W or 5W rating, but can greatly benefit from their use. This principle applies even more strongly to cars which were specified with 20W-40 oils. The use of 0W-40 oil will give similar viscosity at operating temperatures. At extreme cold temperatures 0W-40 will be as little as one eighth as viscous as 20W-40. This will assure superior lubrication until the engine is warmed up.

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