

THE UPS AND DOWNS OF VISCOSITY

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The topic of viscosity has been covered extensively in many technical bulletins and with good reason. The viscosity of a lubricant is its most important physical property and it is this property that defines the very essence of the oil. Viscosity grading systems such as the SAE (Society of Automotive Engineers) for automotive oils and the ISO (International Standards Organisation) for industrial applications have received universal acceptance as a means of classifying lubricants.

Topics relating to viscosity that have been covered in the past include: oil classification systems, how oil works, why there are so many different types of oils, friction and lubrication and how to read a can of oil. Other technical bulletins have touched on how viscosity measurements are made. But why do we actually bother to measure viscosity?

Firstly, as already mentioned, it defines the oil in use so that this can be compared with what has been stated on the submission form. Secondly, changes in viscosity, either up or down, can indicate chemical and physical changes in the oil that may be as a result of a mechanical problem. It is these changes in viscosity and their causes that will be covered in this technical bulletin.

WHAT IS VISCOSITY?

But first, a little revision. Viscosity is essentially a measurement of a fluid's resistance to flow at a specified temperature. However, there are two types of viscosity.

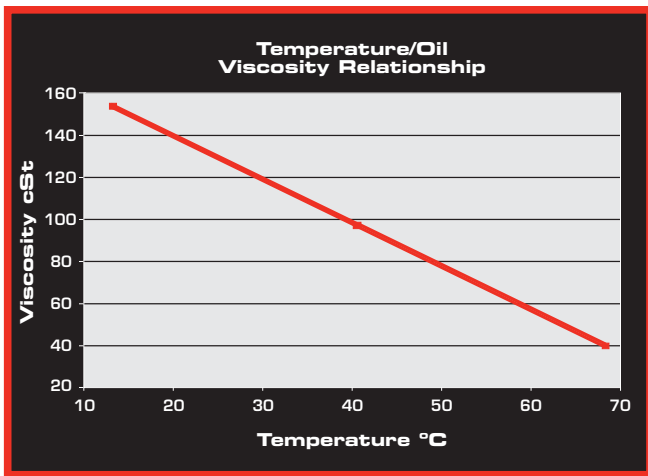
Dynamic or absolute viscosity is defined as the ratio of shear stress to shear rate at a specified temperature. For those of you who want a more rigorous definition, it is the tangential force per unit area required to move one horizontal plane with respect to another at unit velocity when maintained a unit distance apart by the fluid. The SI unit of dynamic viscosity is a Newton second per square metre or Pascal second (N s m^{-2} or Pa s). The non-SI, but acceptable unit, the Poise, is 0.1 N s m^{-2} . Because the dynamic viscosity of real fluids is invariably a fractional quantity, the more usual unit is the centipoise (cP , $10^{-3} \text{ N s m}^{-2}$) and is represented by the Greek letter eta (η).

Dynamic viscosity is important in defining certain low temperature properties of lubricants but is rarely employed in the used oil analysis business or for defining viscosity grades (we shall return to this point later). For a number of very good reasons, the oil analyst is interested in the kinematic viscosity.

Kinematic viscosity is a derived unit and is quite simply the dynamic viscosity of the fluid divided by its density at a specified temperature. It can also be defined as the resistance to flow under the force of gravity. The SI unit is the metre

squared per second also known as the Stoke (m^2s^{-1} or St) and is represented by the Greek letter nu (ν). The more common term is the centistoke (cSt) which is a millimetre squared per second. The preferred temperatures at which these measurements are made are 40°C and 100°C .

It is vitally important that the temperature at which viscosity is measured be noted, as viscosity changes with temperature. As temperature increases, the viscosity decreases as shown in the simplified graph below:

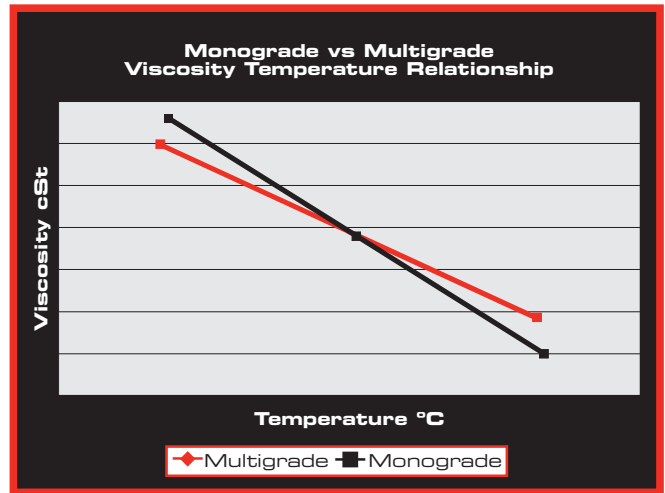


Temperature/Oil Viscosity Relationship

To further complicate matters, different oils thin out at different rates as the temperature increases. This introduces the concept of a viscosity index or VI. The VI of an oil is a unitless number that gives a measure of how quickly the viscosity will change with temperature. Oils with a low VI will thin out more rapidly than oils with a higher VI as temperature increases. A typical monograde engine oil such as an SAE 30 will have a VI of about 95 whilst a multigrade 15W40 oil will have a VI of about 135. The multigrade oil will thin out less than the monograde as temperature increases, thus providing a more stable viscosity profile over a wider range of temperatures, yet both will have a viscosity of about 100 cSt at 40°C .

In the SAE viscosity system, the higher the number, the higher the viscosity; in effect an SAE 15W40 oil behaves like an SAE 15 when it is cold and an SAE 40 when it is hot. This provides adequate protection at operating temperature yet ensures that the oil is not too thick to flow when the engine is cold. In fact, the 'W' actually stands for 'Winter'. The graph at the top of the next column illustrates the relationship between monograde and multigrade oils.

The VI of an oil can be increased in a number of ways. Typical mineral multigrade oils have an additive, VII or viscosity index improver,



Monograde vs Multigrade Viscosity Temperature Relationship (exaggerated)

which is a long chain organic polymer that remains tightly curled up when it is cold. As the temperature increases the polymers uncoil and retard the thinning action of the increase in temperature. Very highly refined mineral oils have a naturally high VI as the refining process removes the components of the crude oil that have poor VI properties. Finally, synthetic lubricants can be chemically engineered to have high viscosity indices. Remember that simply refined crude oils without any additives have a natural VI.

The viscosity index of an oil can be determined by measuring the kinematic viscosity of the oil at two temperatures, usually 40°C and 100°C . Kinematic viscosity is measured using a kinematic viscometer. Typical instruments are shown below.



Typical kinematic viscometers

A silicone oil bath is kept at constant temperature (to within one twentieth of a degree) and a series of tubes are immersed in the bath. The oil flows down the tube under the force of gravity until it reaches an electronic sensor at the bottom of the tube. As the oil passes the sensor a timer is started. A short distance further on is another sensor that

stops the timer as the oil passes it. Based on the bore of the tube and the time it takes the oil to flow between the two sensors, the viscosity can be calculated. A viscosity tube is shown below.



A viscosity tube

This test method is very easy to carry out. It is also quick, cheap, accurate and repeatable. This is not necessarily so when trying to measure dynamic viscosity where a film of oil is placed between two plates and the force required to rotate one plate over the other is measured. The distinct advantages of measuring kinematic viscosity have insured that this is the method of choice. However, dynamic viscosity will probably give a truer reflection of what is actually going on in a real, lubricated system. The kinematic measurement subjects the oil to the very small shearing stress of gravity, whereas dynamic viscosity measurements involve shearing stresses more typical of those encountered in a mechanical system and this in turn can affect the viscosity of the oil in a real situation.

Before we move on, let us consider some of the less common units of kinematic viscosity measurement. Saybolt Universal Seconds (SUS) were popular in the United States and are based on the number of seconds it takes for 60 millilitres of oil to flow through a carefully calibrated orifice. Related to the SUS (or SSU) are the Saybolt Furol Seconds (SFS). This is basically the same as the universal measurement but applies to more viscous fluids. Furol is, in fact, an acronym for 'Fuel and Road Oils'. Degrees Engler were popular in continental Europe and are based on the ratio of time it takes for 200 millilitres of oil to flow through the viscometer to the time taken for the same volume of water to flow at 20°C. Redwood Seconds were used in the United Kingdom and the reading is based on the time taken for 50 millilitres of oil to flow

through the viscometer. There are conversion factors to change between one system and another but the temperature must be stated and it is usually assumed that the oil has a VI of 95.

So, now that we know what we are measuring, why we are measuring it and how we conduct the test - what do the results mean? What is the significance of a viscosity that is too high or too low? What causes viscosities to change?

CAUSES OF VISCOSITY CHANGES

The viscosity of an oil can increase for a number of reasons such as polymerisation, oxidation, evaporative loss of light ends, and formation of carbon and oxide insolubles. Contaminants such as water, air, soot, anti-freeze and the addition of wrong oil can also cause an oil's viscosity to increase. Let us look at each one of these in turn.



Heavily sludged engine oil (soot contamination)

POLYMERISATION

Polymerisation of the oil's base compounds can occur when the oil is subjected to high temperatures for extended periods of time. The base stock of an oil contains a variety of different, yet closely related, organic compounds. High temperatures can cause some of these compounds to stick together chemically, creating higher molecular weight compounds of the same family. This results in a dramatic increase in the viscosity and boiling point of the oil.

OXIDATION

Another effect that is closely related to polymerisation is oxidation, because an increase in oxidation is also caused by high temperature operation. The base stock of an oil can react with oxygen in the atmosphere. This reaction is known as oxidation. This can also lead to

polymerisation but at the same time can promote the formation of organic acids in the oil. The overall effect is an increase in acidity, viscosity and wear rate associated with a decrease in TBN (Total Base Number).

For every 10°C increase in temperature you will double the rate of oxidation and, by logical extension, halve the lifetime of the oil. This situation is not quite as dire as it sounds as oils are blended with additives that combat the effects of high temperatures and acid formation. A question that is often asked is 'What is the maximum temperature that this oil can withstand?' Unfortunately there is no answer as the lifetime of the oil is not only dependent on operating temperature but time as well. So, what we need to know is, how hot and for how long? An engine oil might happily deal with 150°C for an hour or so but degrade severely at 100°C over a longer period of time.

FORMATION OF CARBON AND OXIDE INSOLUBLES

Also related to oxidation is the formation of carbon and oxide insolubles. High temperature operation can cause the formation of a variety of compounds that are insoluble in the oil. Soot is formed when oil is partially oxidised and other oil degradation by-products can form, all of which serve to increase the viscosity of the oil. This effect may also be simply due to an extended oil drain period; even the best oils cannot last forever.

LOSS OF LIGHT ENDS

High temperature operation can also cause thermal degradation of the oil without the presence of oxygen being necessary. As already mentioned, the base oil consists of a variety of closely related compounds. These compounds all have different volatilities (boiling points). If an oil is subjected to prolonged, elevated, but not high temperatures then the lower boiling point components will evaporate. This is known as the loss of light ends. These more volatile components are also the fractions that have lower viscosities so the loss of light ends results in an increase in viscosity.

CONTAMINANTS

Contaminants also play a role in increasing viscosity. Water may have a lower viscosity than oil but when it mixes with the oil it can react with both the base stock and, more importantly, the additives. Stable emulsions can form which create compounds that increase the viscosity of the oil. Water also provides another source of oxygen which can promote oxidation under the right circumstances. The reaction of water with the oil and its additives is known as hydrolysis. A small but measurable amount of water will actually dissolve in oil, then emulsions will form and finally free water will be visible in the oil. The amount of water in each phase depends on the base stock, the additive chemistry and the temperature of the oil.

Air can be found dissolved or free in oil. It can also become entrained (equivalent to an emulsion) and can form a foam. Air acts as a ready supply of oxygen and if it is well mixed with oil it will promote oxidation that will thicken the oil.

In an ideal world the combustion of fossil fuels such as diesel or petrol would lead to the formation of nothing more than carbon dioxide and water vapour. Unfortunately we live in the real world, where fossil fuels are not pure compounds and the combustion process is not 100% efficient. Poor combustion leads to partially oxidised fuel which leads to soot accumulating in the oil. This is why diesel engine oils turn black after a very short period of time. Once again oils are formulated with additives to deal with a certain amount of soot but once the limit has been reached the generation of any further soot will cause the viscosity of the oil to increase. This is known as the dreaded sludging problem which many of you may be familiar with.

Contamination with coolants not only causes a problem due to the presence of water but if the coolant contains glycol this has an extremely detrimental effect on the oil and can cause dramatic thickening of the oil in a very short period of time.

The simplest way to increase the viscosity of the oil is to add another lubricant that has a higher viscosity. Topping up a typical SAE 10W with 20% of an SAE 50 would increase the viscosity by 35%. Finally, if you want to increase the viscosity of your oil, simply forget to change it. All the effects listed here only get worse with time. The longer the oil is in use, the more it degrades and the usual effect of that is for the viscosity to increase. Remember that the additives in your oil are sacrificial. Once they have done their job, that's it. They cannot be regenerated - oil cannot last forever.

THE EFFECTS OF HIGH VISCOSITY

So what are the effects of high viscosity? High viscosity can create viscous drag. This generates more friction which in turn generates more heat, which will accelerate the oxidation process - in effect a vicious circle as opposed to a viscous circle. Inadequate flow to bearings, cavitation, oil whip in journal bearings, energy and power losses, poor defoaming and demulsifying characteristics, fluid backup in drain lines and poor cold-start pumpability can also all result from increased viscosity. Having said all of that, it is often oil with too low a viscosity that can actually do more damage to a component, so what causes an oil's viscosity to decrease?



Low viscosity hydraulic oil

CAUSES OF DECREASED VISCOSITY

There are fewer causes for a decrease in an oil's viscosity, and oils are better equipped to deal with an increase in viscosity as this is an oil's natural physical and chemical tendency with age.

THERMAL CRACKING

Some oils can be subject to a phenomenon known as thermal cracking and this is of particular concern for heat transfer fluids. Thermal cracking can be thought of as the opposite of polymerisation yet both are caused by prolonged exposure to high temperatures. If polymerisation is the sticking together of a number of similar organic compounds to produce new compounds with higher viscosities (and boiling points), then thermal cracking involves the breaking up of the same compounds into smaller pieces. These smaller pieces will have lower viscosities and, more importantly, lower boiling points which result in lower flashpoints and greater volatility. An oil's flashpoint is the minimum temperature at which an oil/air vapour mixture will momentarily support combustion if an external ignition source is introduced. A low flashpoint can have important health and safety implications.

HIGH SHEARING FORCES

Earlier it was mentioned that the viscosity index of an oil can be increased by the addition of certain compounds. Unfortunately these long organic polymers that uncoil when the oil heats up are not completely shear stable. This means that when the compounds are subjected to high shearing forces, such as may be encountered in an automatic transmission, they start to break up resulting in a permanent viscosity loss. Oils that achieve a high VI through the refining process or by virtue of their synthetic base stock are not subject to this phenomenon.

CONTAMINATION

An oil's viscosity may also decrease due to contamination, the most common source of which is fuel dilution. A typical SAE 15W40 engine oil will have a viscosity at 40°C of between 100 and 120 cSt whilst diesel will have a viscosity of between 3 and 5 cSt under the same conditions. Diesel and engine oils are fully miscible in all proportions. The most serious effect fuel dilution has on the oil is to reduce its viscosity and the reduction in viscosity results in a loss of the load bearing ability of the oil. What this ultimately means is that the oil is too thin to keep moving metal surfaces apart and some form of failure or seizure is inevitable. Obviously the seriousness of the failure and the time for it to occur will depend on such things as make, model, application, environment, load factors, oil change period, maintenance procedures, etc. A very rough rule of thumb is that typically 8.5% fuel dilution would drop the viscosity of a 15W40 by about 30% at 40°C and by about 20% at 100°C.

The other effect is less obvious and not as serious, but diesel does not contain any of the additives that oil does, so if you have 10% fuel dilution then essentially you have reduced the concentration of the oil additive package by the same amount. This only becomes serious when the fuel dilution is very high indeed.

ADDING SOLVENTS

Viscosity can also be reduced by the addition of solvents used as flushing and cleaning agents and these need not necessarily be limited to engines. Solvents may also enter the engine through adulterated fuels. Refrigeration compressors can be contaminated with refrigerant gases which will reduce the viscosity, as will any other process gases that become dissolved in the lubricant of any other piece of plant.

ADDING LOWER VISCOSITY GRADE OIL

Finally, as with an increase in viscosity, an oil's viscosity can decrease with the addition of a lower viscosity grade lubricant. Adding 20% of an SAE 10W to an SAE 50 would reduce its viscosity by nearly 30%.

THE EFFECTS OF LOW VISCOSITY

So what are the effects of low viscosity? Excessive wear due to the loss of the load bearing characteristics of the oil has already been mentioned in connection with fuel dilution. Energy losses and an increase in friction due to metal-to-metal contact will also result. The increase in mechanical friction will also increase the amount of heat generated and thereby increase the likelihood of oxidation. One of the functions of a lubricant is to act as a seal; low

viscosity oil does not make a good seal, so both internal and external leakage may be a problem. Low viscosity oils are also more sensitive to particulate contamination as lubricant films are thinner. Finally, a hydrodynamic film in an ideal world is dependent on high speed, high viscosity and low load. This means that if the viscosity is low then high load and/or low speed applications may result in lubricant film failure.

at 40°C and engines should also have their viscosity measured at 100°C.

TROUBLESHOOTING CHANGES IN VISCOSITY

MEASURING AT 40°C vs 100°C

Industry standards dictate that the typical temperatures at which viscosity should be measured are 40°C and 100°C. What are the different advantages of the two temperatures? The measurement at 40°C is useful for the early detection of oxidation, polymerisation and thermal failure of the oil. It is also good for the detection of contaminants such as fuel and refrigerants which will lower the viscosity. The addition of different viscosity oils is more noticeable at the lower temperature. It makes sense to measure viscosity at the temperature that is closest to the actual operating temperature of the machine. Equipment operating at close to ambient temperature should have its viscosities measured at 40°C. Obviously, viscosity measuring instruments that operate closer to ambient temperature are easier to operate in the field or plant.

Measurement at 100°C has advantages in the detection of viscosity index improver shear down and is best suited for components that operate at high temperatures such as internal combustion engines. Both temperatures may be employed where the calculation or change of the VI is important and where multiple objectives need to be achieved. Typically, all samples should have a viscosity measurement

Simply changing the oil because the viscosity is too high or too low is not going to make the problem go away; active troubleshooting is required.

If your viscosity is too high, then check:

- operating temperature
- combustion efficiency
- presence of water or glycol
- aeration
- topping up procedures

If your viscosity is too low, then check:

- the fuel system for malfunction
- the presence of high shearing forces
- high temperature resulting in thermal cracking
- solvent contamination and dissolved gases
- topping up procedures

As has been clearly shown, there is a lot that can go wrong with the viscosity of an oil for many reasons and these can both indicate and result in many different problems. Keeping an oil's viscosity within reasonable upper and lower limits will result in better running equipment, less unplanned breakdowns, lower labour and spare part costs, less downtime and higher profitability. Make sure that viscosities are monitored regularly so that small problems can be corrected before they become major catastrophes.

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