Lubricants' measurements

Aims of the practice: measurement of lubricants' viscosity, familiarization of the viscosity index and its calculation from the data measured during the practice.

Notion, determination, and significance of viscosity

Viscosity is a friction-like internal resistance against fluid motion that always involves relative motion of fluid packages inside the fluid itself. It is a most or, perhaps, the most property of lubricants for application.

According to **Newton's law**, the friction force acting against slipping of fluid layers on each other is proportional with the contacting surfaces, their relative velocity, and inversely proportional with the distance of the slipping layers. The proportionality factor (coefficient) is a measure of viscosity, and is called the dynamic viscosity (η):

$$F = \eta \frac{dv}{dx} A$$

where

F – friction force

η - ('eta') coefficient of internal friction**, i.e. the (dynamic) viscosity**

A – frictional (contacting) surface area

$\frac{dv}{dx}$ is limit value (differential quotient) of the ratio $\frac{\Delta v}{\Delta x}$ where the numerator is the relative velocity of slipping layers, and the denominator is the distance of the layers. This may also be called velocity gradient. This latter term is based on three-dimensional approach of motion described with vectors.

Its measurement is made according to Newton's law, e.g. with turning surfaces (rotational viscosimeters). Its unit is derived from the definition:

$N = \eta \cdot \frac{\frac{m}{s}}{m} \cdot m^2$ hence unit of η is $\frac{N}{m^2}s$. Since $\frac{N}{m^2} = Pa$, **unit** of η is $Pa \cdot s$**.**

Before accepting the SI standard, centipoise (cP) was used: $(1cP = 0.001 Pa \cdot s = 1 mPa \cdot s)$

Some fluid properties are proportional with the ratio of dynamic viscosity to density, rather than with dynamic viscosity itself. Such a property, for example, is the time needed for a given amount of fluid to flow through a narrow tube (capillary). That is why the **notion of kinematic viscosity** (ν), **as ratio of dynamic viscosity to density** is also introduced. Its measurement is done with capillary viscosimeters.

Its unit is $\nu = \frac{Pa \cdot s}{\frac{kg}{m^3}} = \frac{m^2}{s}$. Its more frequently used unit is $\frac{mm^2}{s}$.

Before accepting the SI standard, stokes (St), or centistokes (cSt) was used: $\left(1 cSt = 1 \frac{mm^2}{s}\right)$

What viscosity lube oil is to be used depends of the place of use. The lube forms a lubricant film between the (metal, plastic, etc.) surfaces slipping on each other, thus preventing their direct contact. If the lube cannot stay between the surfaces then the lubrication is not suitable and the parts go wrong prematurely. Quality of lubrication strongly depends on the viscosity.

If the compressing strength between the surfaces is large then a higher viscosity lubricant is needed because low viscosity lube would be pressed out from between the parts. On the other hand, low viscosity lube may be used for low load, like in the case of clock or fine instruments. It is expedient to use a lubricant with the lowest acceptable viscosity because use of higher viscosity lubricant involves higher friction and, therefore, more energy loss. That is why low viscosity lubes are also called energy saving lubes. **Higher viscosity lubricant is needed as well for lubricating parts that move slowly** because the lube has more time to flow out from its place. For lubricating parts moving fast, small viscosity lube may be suitable; for example, quite low viscosity lube, so-called spindle oil, is applied for the fast spinning spindles in textile industry.

Quality of surface elaboration and precision of joints have also effect on viscosity demand. **Lower viscosity oils may be applied to very finely suited surfaces characterized by smaller surface roughness**, whereas higher viscosity lubricant is needed for covering large roughness. That is why lower viscosity lube oils are satisfactorily applied in the novel cars produced with finely elaborated part surfaces and precise joints than in old automobiles, and that is why higher viscosity oils help for run-down machines.

Measuring kinematic viscosity at laboratory practice

So-called capillary viscosimeters are used for measuring kinematic viscosity of lube oils in internationally accepted kinematic viscosity unit (mm^2/s = cSt) applied in crude oil industry.

The oil at given temperature and pressure is let flow through a capillary in a standardized equipment, and the time needed for a given volume to flow out is measured. The principle of the measurement is that the flow time is proportional with the kinematic viscosity of the oil, therefore the flow time multiplied by a proportionality constant characteristic to the particular device provides with the kinematic viscosity. The proportionality constant is called 'instrument constant' or 'device constant' and is determined by a measurement with an oil of known viscosity. This latter operation is called 'calibration' or 'certification'. The instrument constant is determined by some metrological authority.

Ostwald viscosimeter

Ostwald viscosimeter, shown in Figure 1, is one of the known capillary viscosimeters. Various scale (thickness) capillaries are used for measuring different viscosity ranges. Their data and rules for selecting the proper scale are instructed by standards. Thermostats must be applied for precisely setting and keeping the temperature. Any vessel may be used if the temperature of the bath liquid can be controlled during the whole measurement within 0.05 C deviation. Water can be used up to 70 C, and silicon oil can be used at higher temperatures.

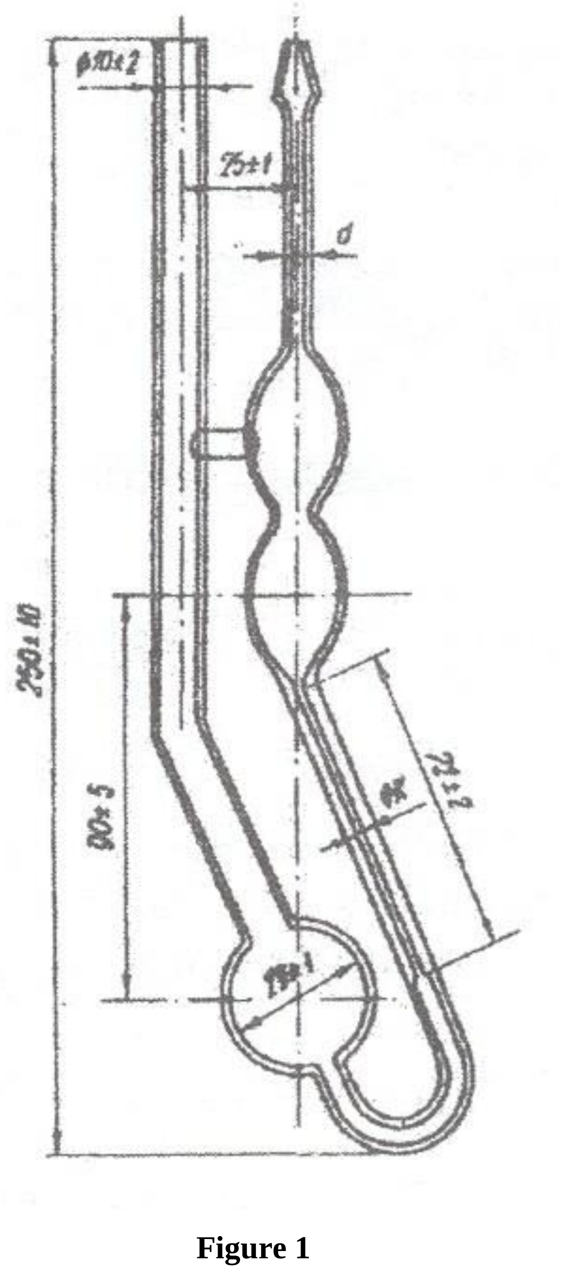

Figure 1

The thermostats applied at the laboratory practice are filled with water for 40 C, and with silicon oil for 100 C measurements. Its cooling is made by tap water, and electric heating is applied, with electronic temperature control. The bath is machine stirred for uniform temperature distribution. Temperature of the bath can be read on a submerged mercury thermometer of scale 0.1 C. The flow time is measured with a stopper of precision at least 0.1 s. The measurement must be started with perfectly clean and dry capillary!

At least three measurements must be made on the same oil, and the deviation between the measured time data should not exceed 0.5% for accepting them. Viscosity is obtained as a product of the measures flow time and the instrument constant written on the actual device:

$$\nu_T = c_T \cdot t$$

where

ν_T is the kinematic viscosity (mm^2/s, i.e. cSt) at temperature T

c_T is instrument constant (mm^2/s^2)

t is mean (average) measured flow time in seconds

Temperature dependence of viscosity

Liquid viscosity decreases with increasing temperature, and increases with decreasing temperature. How much it changes is an important qualifying property of the lube oil. The oil with smaller change of viscosity on temperature change is the more valuable.

According to experiments, double logarithm of kinematic viscosity (log log ν) is approximately linear in simple logarithm of absolute temperature (log T): $\log(\log(\nu)) \approx a + b \cdot \log(T)$ or, in a simpler notation, $\log\log\nu \approx a + b \cdot \log T$.

Therefore, measuring the viscosity at two different temperatures is enough for interpolating or extrapolation to other temperatures.

Several attempts have been made for characterizing the temperature dependence of viscosity with a single number so that lube oils can be compared with each other in a simple way, and these have led to introduction of several absolute and relative qualifying indexes. An example to the absolute qualification is classifying motor oils by grades, whereas and example to relative qualification is viscosity index (VI). The relative qualification is based on the idea that the behavior of the actual oil in changing temperature is related to the behavior of a series of pre-selected basic oils.

Viscosity index

At the time of introducing this notion, API selected the then known best and worst lube oils. (The best was with the smallest sensitivity to temperature change.) The best kind ('paraffinic' basic oils) were named of index 100, whereas the worst kind ('naphthenic' basic oils) were named index 0. These two basic oils are made of crude oils from two different sources. Both kinds include oils with higher and lower viscosity; the index does not characterize the viscosity itself but its **sensitivity to temperature**. Thus there is a series (with different viscosity) of oils with index 0, and there is a series (with different viscosity) of oils with index 100. For qualifying an arbitrary lube oil, its temperature sensitivity is compared to those two, in the two basic series, of which kinematic viscosity **at 100 C** is equal to that of the actual lube oil.

Before presenting the general definition, the interpretation of VI is illustrated with an example of rounded values. For determining the VI of our particular oil, first its kinematic viscosity is measured on 100 C. Suppose the measured kinematic viscosity at 100 C is 6 mm^2/s. Then the corresponding oil, i.e. one whose kinematic viscosity at 100 C is also 6 mm^2/s, is selected from the series of index 0. The other corresponding oil, i.e. one whose kinematic viscosity at 100 C is also 6 mm^2/s, is also selected from the series of index 100. Thus, we deal with three oils, all having kinematic viscosity 6 mm^2/s at 100 C:

- Our particular oil (oil U) with unknown VI.
- The selected oil (oil L) with VI=0.
- The selected oil (oil H) with VI=100.

Now all three oils are cooled down to 40 C, and their viscosity are measured at that temperature. Naturally, each of the three viscosities will be higher than that at 100 C, but viscosity of the worst oil increases most. Suppose that viscosity of oil L increases to 25 mm^2/s (this will be denoted by L, referring to the Lowest index), the viscosity of oil H increases to 20 mm^2/s only (this will be denoted by H, referring to the Highest index), and the viscosity of our particular oil U increases to 21 mm^2/s (this will be denoted by U, referring to the Unknown index).

Having these three new viscosities (25 mm^2/s, 20 mm^2/s, and 21 mm^2/s), scale the distance between 25 mm^2/s and 20 mm^2/s (the distance is 5 mm^2/s) from 0 to 100, and measure the actual one (21 mm^2/s) to this scale. You find that the actual index is 80 (because each 1 mm^2/s counted down from 25 mm^2/s increments the index by 20).

In formula, VI is defined in this case as $\mathrm{VI} = \dfrac{25\frac{\mathrm{mm}^2}{\mathrm{s}} - 21\frac{\mathrm{mm}^2}{\mathrm{s}}}{25\frac{\mathrm{mm}^2}{\mathrm{s}} - 20\frac{\mathrm{mm}^2}{\mathrm{s}}}\cdot 100 = \dfrac{4\frac{\mathrm{mm}^2}{\mathrm{s}}}{5\frac{\mathrm{mm}^2}{\mathrm{s}}}\cdot 100 = 80$.

The general formula is then

$$\mathrm{VI} = \frac{\mathrm{L} - \mathrm{U}}{\underbrace{\mathrm{L} - \mathrm{H}}_{\mathrm{D}}}\cdot 100$$

where

VI is viscosity index

U is kinematic viscosity of the examined oil at 40 C (mm^2/s).

L is kinematic viscosity of the oil at 40 C (mm^2/s) with viscosity index 0 and kinematic viscosity at 100 C equals with that of the examined oil.

H is kinematic viscosity of the oil at 40 C (mm^2/s) with viscosity index 100 and kinematic viscosity at 100 C equals with that of the examined oil.

D=L-H is a difference of viscosities at 40 C.

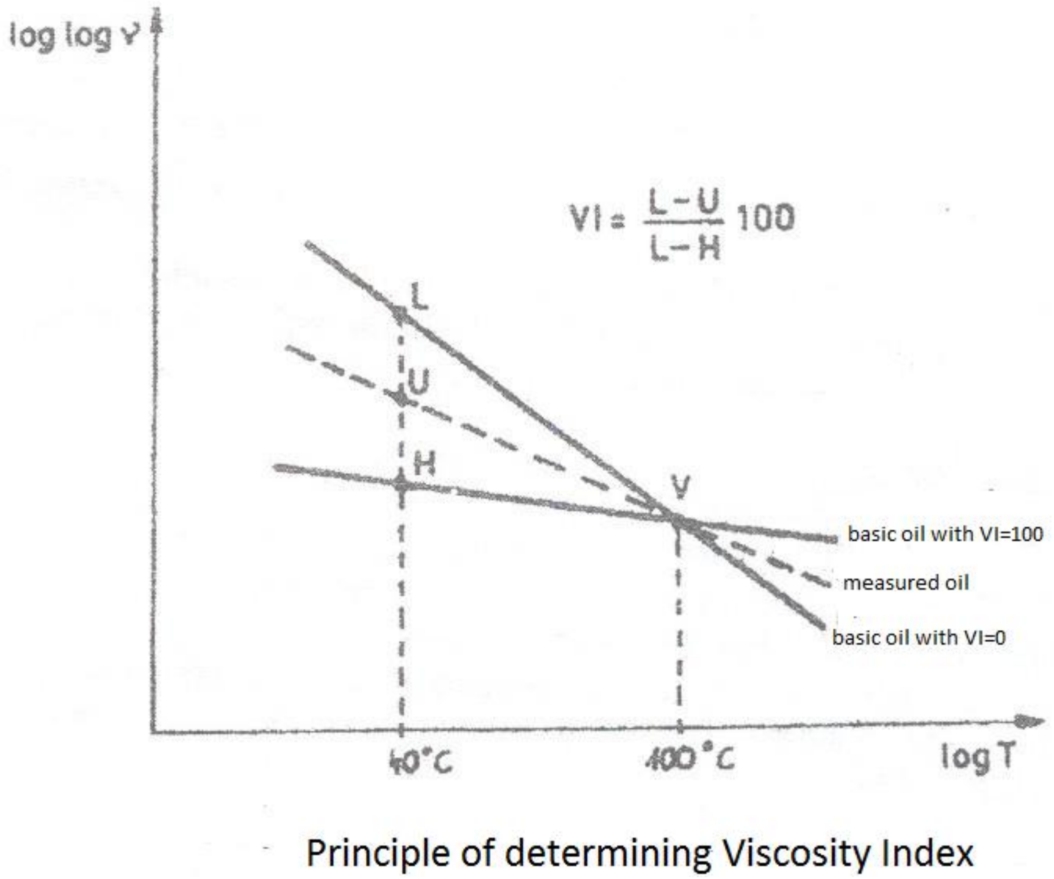

Figure 2

Viscosity L and H need not be actually measured because they are already measured once and for ever. Kinematic viscosity of the basic oils with index 0 and 100 and on temperatures 100 C and 40 C are listed in tables. Thus, for a given viscosity at 100 C, the corresponding values of L, U, and D can be read out from a table.

If the actual viscosity cannot be found in the table because it shows more significant digits than the values listed in the table then interpolation can be applied between the neighboring rows of the table for obtaining L, D, and H.

The calculated VI value must be rounded to integer numbers.

Since the time of defining VI, even better lube oils have been synthesized so that the actual VI can be larger than 100. (Moreover, VI can be negative, as well.) Modern motor oils may have VI≈200. For cases VI>100, the above definition is not applied but a so-called ' Viscosity Index Extension ' (VI_E) is defined:

$$VI_E = \frac{10^N - 1}{0.00715} + 100$$

where

$$N = \frac{\log(H) - \log(U)}{\log(\nu_{100°C})}$$, based on the definition: $\nu_{100°C}^{N} = \frac{H}{U}$,

$\nu_{100°C}$ is kinematic viscosity of the examined oil at 100 °C,

H and U are as earlier.

Winter and summer grading of motor oils according to SAE J 300

Viscosity index (VI), characterizing temperature dependence of viscosity of lube oil, is exclusively used by experts only because it is too complex a notion for public. That is why SAE introduced 'winter' grades for characterizing behavior of lube oils in cold weather. These winter grades are defined by viscosity at low temperatures and pumpability limit temperatures belonging to 60000 mPas viscosity that defines a cold flow property of the oil (see Figure 3). The winter and summer grades are shown in Table 1.

Table 1. Viscosity of motor oils by SAE J300

Winter motor oils		Summer motor oils			
SAE viscosity class	pumpability limit temperature*	SAE viscosity class	Upper temperature of environment for use	minimum kinematic viscosity at 100 C, mm^2/sec	maximum kinematic viscosity at 100 C, mm^2/sec
0 W	-40 C	20	+25 C	5.6	9.3
5 W	-35 C	30	+35 C	9.3	12.5
10 W	-30 C	40	+45 C	12.5	16.3
15 W	-25 C	50	+55 C	16.3	21.9
20 W	-20 C	60	+65 C	21.9	26.1
25 W	-15 C				

*This is the temperature at which the viscosity of the oil reaches 60000 mPa·s.

Minimum and maximum viscosity values are shown for the summer grades. The selection is facilitated by providing a limit temperature of application environment. Lower SAE grade means lower viscosity oil. Selecting higher summer grade at heavy load is expedient for avoiding insufficient lubrication due to decreased viscosity.

Modern motor oils satisfy both winter and summer demands (multigrade lube oils). Usual notation is, for example: 5W/30, meaning an oil pumpable down to -35 C and usable up to +35 C environment temperature.

Labor practice tasks

Measuring motor oils viscosity at 40 C and at 100 C

- Check the position of the viscosimeter filled with oil in the thermostating bath. It should be positioned that the bath liquid covers the upper bulb, and the stems of the viscosimeter are vertical.
- Bath temperature must be set with 0.05 C accuracy.
- Wait for stabilizing the bath temperature and for the sample to take over the temperature of the bath. This takes at least 10 minutes. Look after that no bubbles are formed in the viscosimeter during the whole measurement process!
- After reaching steady temperature, a rubber tube is pulled on the upper end of the narrower tube of the viscosimeter, and the upper liquid level of the oil sample is sucked up over the upper mark between the two bulbs, then the rubber tube used for sucking is removed. Beware, the glass device is rather fragile, do not pull the rubber tube on the glass tube too deeply, but barely only.
- The liquid level slowly decreases in the bulb. The stopper is started when the level reaches the upper mark between the two bulbs, and stopped when it reaches the lower mark. Thus the flow

time of oil liquid of standard volume of the lower bulb delimited by the marks is measured. (Find the marks and try out the stopper before starting the measurements.)

- The flow times are measured in thermostats set to two temperatures (40 °C and 100 °C).
- 3 measurements are performed at both temperatures, and the average flow times are used for calculation. Put down a note of the instrument constants of the applied viscosimeters.

Work up of the measured data

- Calculate the lube oil viscosity at 40 C and at 100 C using the instrument constants.
- Calculate the viscosity index of the sample. For this aim, use the standard stored in the lab. The standard contains L and H values for kinematic viscosities at 100 C. **Taking the standard out of the lab is prohibited.**
- If Viscosity Index is higher than 100 then Viscosity Index Extended is to be calculated as well. This is expected a larger value than VI.
- Classify the sample motor oil to a summer SAE grade according to its viscosity at 100 C.
- Plot the temperature dependence of the viscosity of sample oil in a log log kinematic viscosity against log absolute temperature (in Kelvin) diagram.
- Determine the motor oil's winter SAE grade by reading the plot.

Bring to the lab practice: graph paper, ruler, pen, pencil, eraser, hand calculator able to calculate logarithm.

Example calculation of viscosity index

Viscosity of the sample oil is measured at both 40 C and 100 C. The measured data are typeset in boldface characters in the table below:

sample identity number (written on the bottle containing the sample)		72	72
temperature (°C)		100	40
instrument constant of the viscosimeter (written on the viscosimeter) (mm²/s²)		0.1084	0.8310
measured flow time values (sec)	t1	**125.92**	**99.98**
	t2	**125.49**	**100.54**
	t3	**125.79**	**100.35**
t average (sec)	= (t1+t2+t3)/3	125.73	100.29
viscosity (mm²/s) = t_average * instrument_constant		13.6295	83.34099
viscosity rounded (The average is calculated from a product and is rounded to so many significant digits as found in the smallest precision value. In the present case both 0.1084 and 0.8310 have four significant digits.)		13.63	83.34

A part of the applied standard is shown below:

Kinematic viscosity at 100 °C (mm^2/s = cSt)	L (mm^2/s = cSt)	H (mm^2/s = cSt)
13.0	231.9	121.5
13.1	235.0	122.9
13.2	238.1	124.2
13.3	241.2	125.6
13.4	244.3	127.0
13.5	247.4	128.4
13.6	250.6	129.8
13.7	253.8	131.2
13.8	257.0	132.6
13.9	260.1	134.0
14.0	263.3	135.4

L and H values are looked for in the table that meet the viscosity measured at 100 C. U in the formula is the measured viscosity of our sample at 40 C.

There is no viscosity 13.63, but 13.6 and 13.7 only, in the table. Therefore, interpolation must be applied.

Difference in L belonging to (13.7-13.6)=0.1 is (253.8-250.6)=3.2; the difference belonging to 0.01 is 3.2/10=0.32 .

Difference over 0.03 is 3*0.32=0.96, this is rounded for a single decimal fraction: 1.0. Therefore, L belonging to 13.36 is L = 250.6+1.0= 251.6 mm^2/s.

In the same way, H = 129.8+(131.2-129.8)/10*3 = 129.8+0.4=130.2 mm^2/s.

U is measured: U=83.34 mm^2/s.

Viscosity Index = (L-U)/(L-H)*100=(251.6-83.3)/(251.6-130.2)*100 =138.63, but Viscosity Index must be rounded to integer value, thus VI = 139.

The calculated VI > 100, therefore VI_E must also be calculated.

$$N = \frac{\log(130.2) - \log(83.34)}{\log(13.63)} = 0.1707787$$

$$VI_E = \frac{10^{0.1707787} - 1}{0.00715} + 100 = 167.3 \approx 167$$

You can see that $VI_E > VI$.

Since VI>100, it probably is a motor oil (but one cannot be sure). Assuming it being a motor oil, it is of grade SAE 40 (between 12.5 and 16.3 mm^2/s in the Table of SAE viscosity grades).

Determining winter / summer SAE grades of motor oil

The summer grade can be read from Table 1.

For determining the winter grade, first plot the double logarithm (of base 10) in function of logarithm (of base 10) of absolute temperature (in Kelvin), see Figure 3. Plot the two measured points (first recalculate 40 C and 100 C to Kelvin). Connect the two points with a straight line. Draw the horizontal line at 60000 mPa·s (recalculate log log value first). Find the cross section of this horizontal line with the straight line defined by the two measured points. Project this intersection point to the horizontal axis to obtain the (logarithm of the) limit temperature of pumpability, and then the winter grade from Table 1.

Construct the diagram in such a way that it stretches over the whole sheet. Scale the axes of the diagram in such a way that it can conveniently be read, and be as precise as possible. Pay attention to fit the applied number of significant digits in calculating logarithms to the opportunity of plotting.

Sample check test questions before the practices:

- Newton law of viscosity, with formula, and interpretation of the applied notation
- How does kinematic viscosity differ from dynamic viscosity?
- Units of dynamic and kinematic viscosities
- What information on the lube oil is carried by Viscosity Index?
- Which oil of Viscosity Indexes VI = 95 and VI = 110 is the better according to the temperature dependence?
- What does the classification 5W/30 means related at a motor oil?
- What kind of oils are the multigrade oils?
- Which oil has lower viscosity: SAE 30 or SAE 40 ?
- Why is it expedient to plot double logarithm of the kinematic viscosity of the lube against logarithm of absolute temperature?

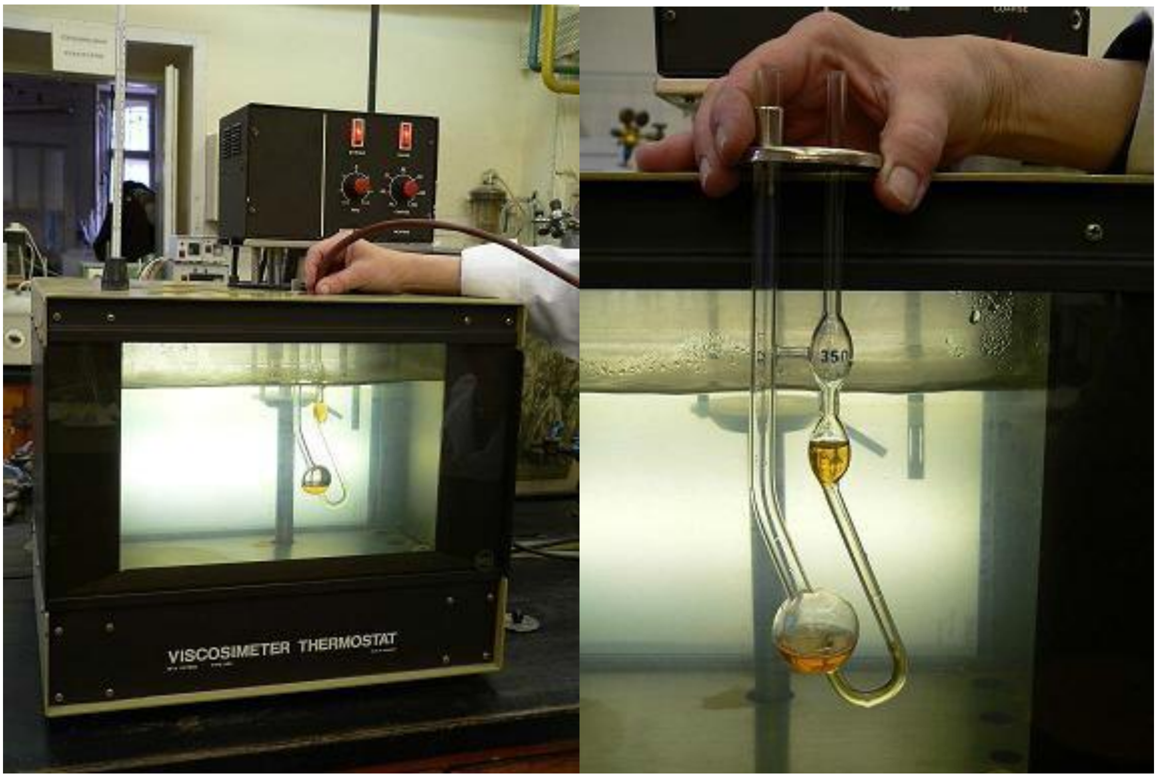

Figure 1. Capillary viscosimeter in thermostating bath

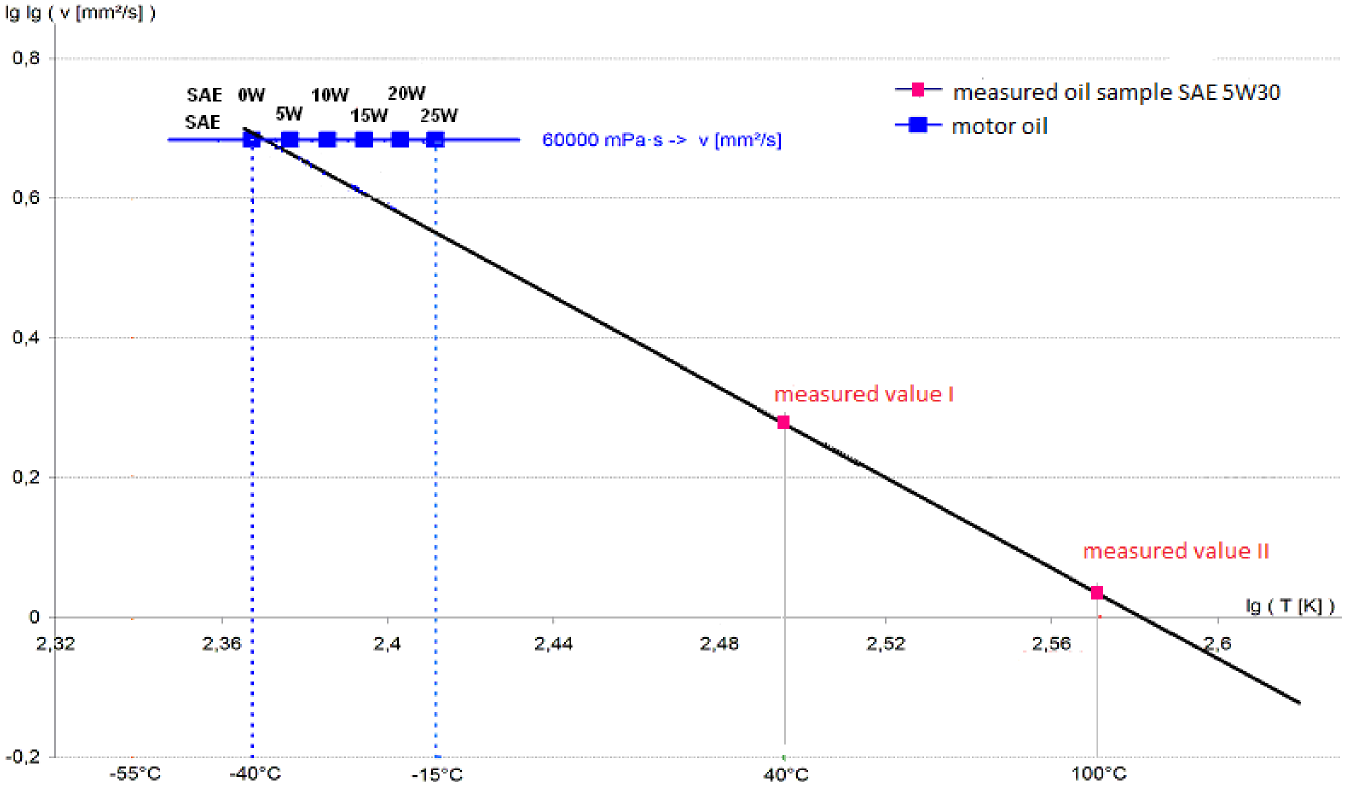

Figure 3. Graphical determination of SAE winter grade of motor oils, based on kinematic viscosity measured at 40 C and 100 C