Pearson BTEC Level 4 Higher Nationals in Engineering (RQF)

Unit 11: Fluid Mechanics

Unit Workbook 2

in a series of 4 for this unit

Learning Outcome 2

Viscosity

Contents

INTRODUCTION

Examine the operating principles and limitations of viscosity measuring devices

- *Viscosity in fluids:*
    - Dynamic and kinematic viscosity definitions.
    - Characteristics of Newtonian fluids.
    - Temperature effects on viscosity.
    - Classification of non-Newtonian fluids.
- *Operating principles and limitations:*
    - Operating principles of viscometers.
    - Converting results acquired from viscometers into viscosity values.

GUIDANCE

This document is prepared to break the unit material down into bite size chunks. You will see the learning outcomes above treated in their own sections. Therein you will encounter the following structures;

Purpose Explains *why* you need to study the current section of material. Quite often learners are put off by material which does not initially seem to be relevant to a topic or profession. Once you understand the importance of new learning or theory you will embrace the concepts more readily.

Theory Conveys new material to you in a straightforward fashion. To support the treatments in this section you are strongly advised to follow the given hyperlinks, which may be useful documents or applications on the web.

Example The examples/worked examples are presented in a knowledge-building order. Make sure you follow them all through. If you are feeling confident then you might like to treat an example as a question, in which case cover it up and have a go yourself. Many of the examples given resemble assignment questions which will come your way, so follow them through diligently.

Question Questions should not be avoided if you are determined to learn. Please do take the time to tackle each of the given questions, in the order in which they are presented. The order is important, as further knowledge and confidence is built upon previous knowledge and confidence. As an Online Learner it is important that the answers to questions are immediately available to you. Contact your Unit Tutor if you need help.

Challenge You can really cement your new knowledge by undertaking the challenges. A challenge could be to download software and perform an exercise. An alternative challenge might involve a practical activity or other form of research.

Video Videos on the web can be very useful supplements to your distance learning efforts. Wherever an online video(s) will help you then it will be hyperlinked at the appropriate point.

2.1 Viscosity

Viscosity is a fluid's resistance to deformation under shear stresses.

Viscosity is an important property of any fluid, as it also helps determine its behaviour and motion against solid boundaries (such as pipes, gears, sliding contacts etc.). The viscosity is determined by the inter-molecular friction that is seen when one layer slides over the other. Or to put it simply, ***viscosity is how runny the fluid is***. The higher the viscosity, the thicker, and less runny, the fluid is.

It is very important to note that viscosity is temperature dependent. When considering a shortlist of fluids to a given application, it is vital that the temperature of the system is also considered.

2.1.1 Dynamic Viscosity

Dynamic viscosity is the fluid's resistance to flow when an external force is applied. Dynamic viscosity can be thought of as the tangential force per unit area required to move one plane (layer) of fluid with respect to another. The velocity between layers of a laminar fluid moving in straight parallel lines for a Newtonian fluid can be seen in Fig.2.1.

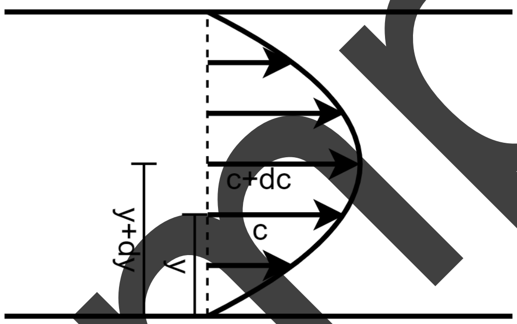

Figure 2.1: Velocity between layers of a laminar fluid

The shear stress τ can be defined by Eq.2.1, where μ is the dynamic viscosity, c is the velocity of the fluid, y is the height from the surface. dc/dy is also known as the "shear rate".

$$\tau = \mu \frac{dc}{dy} \qquad (2.1)$$

The SI units for dynamic viscosity is $\text{Pa} \cdot \text{s}$, the values used are typically very low (e.g., the dynamic viscosity of water at $20°\text{C}$ is $0.0010005\ \text{Pa} \cdot \text{s}$. More commonly the units that are used are the Poise, P, or centipoise, cP, where $10\ \text{P} = 1\ \text{Pa} \cdot \text{s}$, therefore the dynamic viscosity of water at $20°\text{C}$ is $0.010005\ \text{P}$ or $1.0005\ \text{cP}$.

2.1.2 Kinematic Viscosity

Kinematic viscosity is the fluid's resistive flow under its own weight (no external forces are applied, just gravity). The substance with the highest kinematic viscosity is tar pitch, which, despite appearing to be a solid and even shatters when it is hit with a hammer, is actually an incredibly viscous liquid, and will drip roughly once every ten years. An experiment widely recognised as the longest running in the University of Queensland, Australia, is analysing the drip of tar pitch and began in 1927. Since the drip occurs around once every ten years, it has never actually been seen; the last time it did drip, the webcam failed and missed it.

Kinematic viscosity, ν, can be calculated using Eq.2.2, where ρ is the density of the fluid

2.1.4.1 $\mathrm{VI} < 100$

In the majority of cases, and for examples within this unit we will only be looking at lubricants with a Viscosity Index (VI) of less than 100.

To calculate the VI, there are two pieces of information which must be known from the start; the Kinematic Viscosity (KV) at 40°C and at 100°C. The KV at 40°C is noted as U and the KV at 100°C is noted as Y in the following method.

If the value of KV at 100°C is between 2 cSt and 70 cSt then the table opposite is used to look up the corresponding values of 'L' and 'H', these letters merely signify some constants of viscosity at certain predefined temperatures. If the KV at 100°C is above the value of 70 cSt then the table is not used to find 'L' and 'H', but rather a separate formula is used, as follows:

$$\mathrm{L} = 0.8353\mathrm{Y}^2 + 14.67\mathrm{Y} - 216 \quad (2.3)$$

$$\mathrm{H} = 0.1684\mathrm{Y}^2 + 11.85\mathrm{Y} - 97 \quad (2.4)$$

The viscosity index in either case is then calculated using Eq.2.5:

$$\mathrm{VI} = 100\frac{\mathrm{L} - \mathrm{U}}{\mathrm{L} - \mathrm{H}} \quad (2.5)$$

2.1.4.2 $VI > 100$

In the rare case that lubricants have a viscosity index greater than 100, then the following steps need to be taken.

1. Determine the kinematic viscosity of the sample at 40°C and 100°C
2. Determine the value of H
    i. If $2\ \mathrm{mm}^2/s < \mathrm{Y} < 70\ \mathrm{mm}^2/s$, the ATSM standards can be used; these values are shown in Table 2.1.
    ii. If $70\ \mathrm{mm}^2/s < Y$, then H is calculated using Eq.2.4:
3. The viscosity index is therefore given as Eq.2.6:

$$\mathrm{VI} = \frac{10^{\mathrm{N}} - 1}{0.00715} + 100 \quad (2.6)$$

Where:

$$\mathrm{N} = \frac{\log_{10}\mathrm{H} - \log_{10}\mathrm{U}}{\log_{10}\mathrm{Y}} \quad (2.7)$$

Table 2.1: ATSM values for L and H for the sample oil of viscosity between $2 - 70 mm^2/s$

Kinematic Viscosity at 100°C, mm^2/s (cSt)	L	H
2.00	7.994	6.394
2.10	8.640	6.894
2.20	9.309	7.410
2.30	10.00	7.944
2.40	10.71	8.496
2.50	11.45	9.063
2.60	12.21	9.647
2.70	13.00	10.25
2.80	13.80	10.87
2.90	14.63	11.50
3.00	15.49	12.15
3.10	16.36	12.82
3.20	17.26	13.51
3.30	18.18	14.21
3.40	19.12	14.93
3.50	20.09	15.66
3.60	21.08	16.42
3.70	22.09	17.19
3.80	23.13	17.97
3.90	24.19	18.77
4.00	25.32	19.56
4.10	26.50	20.37
4.20	27.75	21.21
4.30	29.07	22.05
4.40	30.48	22.92
4.50	31.96	23.81
4.60	33.52	24.71
4.70	35.13	25.63
4.80	36.79	26.57
4.90	38.50	27.53
5.00	40.23	28.49
5.10	41.99	29.46
5.20	43.76	30.43
5.30	45.53	31.40
5.40	47.31	32.37
5.50	49.09	33.34
5.60	50.87	34.32
5.70	52.64	35.29
5.80	54.42	36.26
5.90	56.20	37.23
6.00	57.97	38.19
6.10	59.74	39.17
6.20	61.52	40.15
6.30	63.32	41.13
6.40	65.18	42.14
6.50	67.12	43.18
6.60	69.16	44.24
6.70	71.29	45.33
6.80	73.48	46.44
6.90	75.72	47.51

Kinematic Viscosity at 100°C, mm^2/s (cSt)	L	H
7.00	78.00	48.57
7.10	80.25	49.61
7.20	82.39	50.69
7.30	84.53	51.78
7.40	86.66	52.88
7.50	88.85	53.98
7.60	91.04	55.09
7.70	93.20	56.20
7.80	95.43	57.31
7.90	97.72	58.45
8.00	100.0	59.60
8.10	102.3	60.74
8.20	104.6	61.89
8.30	106.9	63.05
8.40	109.2	64.18
8.50	111.5	65.32
8.60	113.9	66.48
8.70	116.2	67.64
8.80	118.5	68.79
8.90	120.9	69.94
9.00	123.3	71.10
9.10	125.7	72.27
9.20	128.0	73.42
9.30	130.4	74.57
9.40	132.8	75.73
9.50	135.3	76.91
9.60	137.7	78.08
9.70	140.1	79.27
9.80	142.7	80.46
9.90	145.2	81.67
10.0	147.7	82.87
10.1	150.3	84.08
10.2	152.9	85.30
10.3	155.4	86.51
10.4	158.0	87.72
10.5	160.6	88.95
10.6	163.2	90.19
10.7	165.8	91.40
10.8	168.5	92.65
10.9	171.2	93.92
11.0	173.9	95.19
11.1	176.6	96.45
11.2	179.4	97.71
11.3	182.1	98.97
11.4	184.9	100.2
11.5	187.6	101.5
11.6	190.4	102.8
11.7	193.3	104.1
11.8	196.2	105.4
11.9	199.0	106.7

Kinematic Viscosity at 100°C, mm^2/s (cSt)	L	H
12.0	201.9	108.0
12.1	204.8	109.4
12.2	207.8	110.7
12.3	210.7	112.0
12.4	213.6	113.3
12.5	216.6	114.7
12.6	219.6	116.0
12.7	222.6	117.4
12.8	225.7	118.7
12.9	228.8	120.1
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
14.1	266.6	136.8
14.2	269.8	138.2
14.3	273.0	139.6
14.4	276.3	141.0
14.5	279.6	142.4
14.6	283.0	143.9
14.7	286.4	145.3
14.8	289.7	146.8
14.9	293.0	148.2
15.0	296.5	149.7
15.1	300.0	151.2
15.2	303.4	152.6
15.3	306.9	154.1
15.4	310.3	155.6
15.5	313.9	157.0
15.6	317.5	158.6
15.7	321.1	160.1
15.8	324.6	161.6
15.9	328.3	163.1
16.0	331.9	164.6
16.1	335.5	166.1
16.2	339.2	167.7
16.3	342.9	169.2
16.4	346.6	170.7
16.5	350.3	172.3
16.6	354.1	173.8
16.7	358.0	175.4
16.8	361.7	177.0
16.9	365.6	178.6

Kinematic Viscosity at 100°C, mm^2/s (cSt)	L	H
17.0	369.4	180.2
17.1	373.3	181.7
17.2	377.1	183.3
17.3	381.0	184.9
17.4	384.9	186.5
17.5	388.9	188.1
17.6	392.7	189.7
17.7	396.7	191.3
17.8	400.7	192.9
17.9	404.6	194.6
18.0	408.6	196.2
18.1	412.6	197.8
18.2	416.7	199.4
18.3	420.7	201.0
18.4	424.9	202.6
18.5	429.0	204.3
18.6	433.2	205.9
18.7	437.3	207.6
18.8	441.5	209.3
18.9	445.7	211.0
19.0	449.9	212.7
19.1	454.2	214.4
19.2	458.4	216.1
19.3	462.7	217.7
19.4	467.0	219.4
19.5	471.3	221.1
19.6	475.7	222.8
19.7	479.7	224.5
19.8	483.9	226.2
19.9	488.6	227.7
20.0	493.2	229.5
20.2	501.5	233.0
20.4	510.8	236.4
20.6	519.9	240.1
20.8	528.8	243.5
21.0	538.4	247.1
21.2	547.5	250.7
21.4	556.7	254.2
21.6	566.4	257.8
21.8	575.6	261.5
22.0	585.2	264.9
22.2	595.0	268.6
22.4	604.3	272.3
22.6	614.2	275.8
22.8	624.1	279.6
23.0	633.6	283.3
23.2	643.4	286.8
23.4	653.8	290.5
23.6	663.3	294.4
23.8	673.7	297.9

Kinematic Viscosity at 100°C, mm^2/s (cSt)	L	H
24.0	683.9	301.8
24.2	694.5	305.6
24.4	704.2	309.4
24.6	714.9	313.0
24.8	725.7	317.0
25.0	736.5	320.9
25.2	747.2	324.9
25.4	758.2	328.8
25.6	769.3	332.7
25.8	779.7	336.7
26.0	790.4	340.5
26.2	801.6	344.4
26.4	812.8	348.4
26.6	824.1	352.3
26.8	835.5	356.4
27.0	847.0	360.5
27.2	857.5	364.6
27.4	869.0	368.3
27.6	880.6	372.3
27.8	892.3	376.4
28.0	904.1	380.6
28.2	915.8	384.6
28.4	927.6	388.8
28.6	938.6	393.0
28.8	951.2	396.6
29.0	963.4	401.1
29.2	975.4	405.3
29.4	987.1	409.5
29.6	998.9	413.5
29.8	1011	417.6
30.0	1023	421.7
30.5	1055	432.4
31.0	1086	443.2
31.5	1119	454.0
32.0	1151	464.9
32.5	1184	475.9
33.0	1217	487.0
33.5	1251	498.1
34.0	1286	509.6
34.5	1321	521.1
35.0	1356	532.5
35.5	1391	544.0
36.0	1427	555.6
36.5	1464	567.1
37.0	1501	579.3
37.5	1538	591.3
38.0	1575	603.1
38.5	1613	615.0
39.0	1651	627.1
39.5	1691	639.2
40.0	1730	651.8
40.5	1770	664.2
41.0	1810	676.6
41.5	1851	689.1
42.0	1892	701.9

Kinematic Viscosity at 100°C, mm^2/s (cSt)	L	H
42.5	1935	714.9
43.0	1978	728.2
43.5	2021	741.3
44.0	2064	754.4
44.5	2108	767.6
45.0	2152	780.9
45.5	2197	794.5
46.0	2243	808.2
46.5	2288	821.9
47.0	2333	835.5
47.5	2380	849.2
48.0	2426	863.0
48.5	2473	876.9
49.0	2521	890.9
49.5	2570	905.3
50.0	2618	919.6
50.5	2667	933.6
51.0	2717	948.2
51.5	2767	962.9
52.0	2817	977.5
52.5	2867	992.1
53.0	2918	1007
53.5	2969	1021
54.0	3020	1036
54.5	3073	1051
55.0	3126	1066
55.5	3180	1082
56.0	3233	1097
56.5	3286	1112
57.0	3340	1127
57.5	3396	1143
58.0	3452	1159
58.5	3507	1175
59.0	3563	1190
59.5	3619	1206
60.0	3676	1222
60.5	3734	1238
61.0	3792	1254
61.5	3850	1270
62.0	3908	1286
62.5	3966	1303
63.0	4026	1319
63.5	4087	1336
64.0	4147	1352
64.5	4207	1369
65.0	4268	1386
65.5	4329	1402
66.0	4392	1419
66.5	4455	1436
67.0	4517	1454
67.5	4580	1471
68.0	4645	1488
68.5	4709	1506
69.0	4773	1523
69.5	4839	1541
70.0	4905	1558

2.2 Viscometers

Viscometers are used to measure the viscosity of the fluid, and there are several types that exist.

2.2.1 Capillary Viscometers

Otherwise known as u-tube or glass viscometers, shown in Fig.2.4. These are the most common viscometers, they are cheap and relatively easy to use, and best suited for transparent or translucent liquids. The method is simple, use suction to bring the fluid up to the start mark (or ideally further past it). Once the suction is removed, the fluid will start to flow downwards.

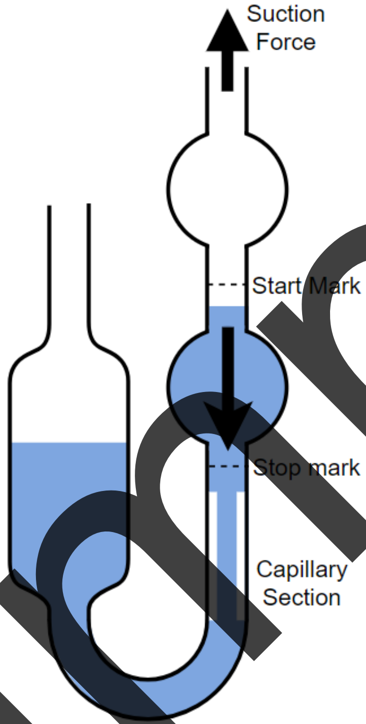

Figure 2.4: Capillary viscometers

The viscosity is measured by calculating the time it takes for the fluid to pass from the start mark to the stop mark. The equation used to calculate the kinematic viscosity of the fluid is given by Eq.2.8, where t is the time taken for the fluid to pass between the two marks, and K is the capillary constant of the viscometer, which is calibrated by measuring a reference liquid of known viscosity.

$$v = K_c \cdot t \quad (2.8)$$

tar pitch), and so rotational viscometers employ a motor to add a rotational driving force. Rotational viscometers can apply two different principles to calculate viscosity:

- Couette Principle
- Searle Principle

Viscometers also measure torque using two different systems.

- Servo systems
- Spring systems

2.2.3.1 Couette Principle

The Couette principle relies on a bob to be suspended in a container filled with the test fluid. In this case, the driving force is acting on the container itself, meaning that the bob is the stationary frame of reference in the system (shown in Fig.2.6). This design avoids any problems with turbulent flow, but it is rarely used in commercial applications as it can be difficult to ensure that the container is well insulated and sealed in the rotating cup.

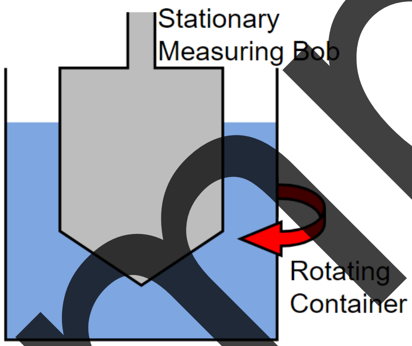

Figure 2.6: Couette principle rotational viscometer

2.2.3.2 The Searle Principle

The Searle principle holds the container stationary, and instead spins the measuring bob (as can be seen in Fig.2.7). In this case, the viscosity is proportional to the motor torque that is required for turning the bob against the resistive viscous forces of the fluid. These are much more common viscometers; however, the measuring bob must be kept at a low enough velocity to ensure that the flow in the container does not become turbulent.

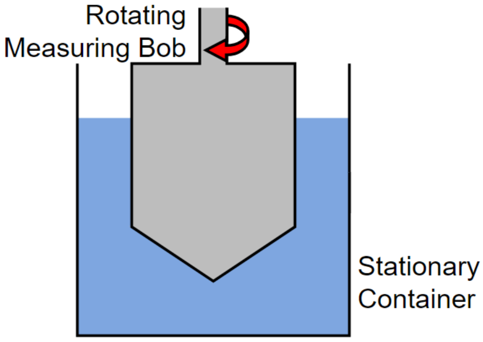

Figure 2.7: Searle principle rotational viscometer

2.2.4 Orifice Viscometers

Orifice viscometers are used in the oil industry because of their simplicity and ease of use. The system consists of a reservoir, an orifice and a receiver. The method is simple; the sample fluid is poured into the reservoir, which is temperature controlled in a water bath. Once the sample fluid has reached the desired temperature (that of the water bath), a valve at the base of the reservoir is opened and the time taken for a specific amount of sample fluid to flow out of the orifice is measured. While the industry has several types of orifice viscometers, this workbook will only look at the Saybolt and Redwood viscometers.

Other orifice viscometers include:

- *Engler viscometers*
- *Ford viscosity cup viscometer*
- *Shell viscosity cup viscometer*
- *Zahn cup viscometer*

2.2.4.1 Saybolt Viscometer

A schematic of the Saybolt viscometer is shown in Fig.2.9. A practical system would most likely have a thermometer in both the water bath and the sample fluid reservoir, as a sure way to make sure that the temperature is controlled - something that isn't accurately controlled in comparison to the capillary, falling sphere or rotational viscometers. Since this system analyses the flow rate of the fluid with only a force due to gravity acting on the fluid, the Saybolt viscometer calculates the kinematic viscosity.

The Saybolt viscometer gives its own unit of viscosity, "Saybolt seconds". This is the time it takes for $60\ \mathrm{ml}$ to pour into the receiver, whilst it is not as scientific as $\mathrm{Pa \cdot s}$, it is a valid measurement of viscosity. Most standards analyse the viscosity in Saybolt seconds at $100^{\circ}\mathrm{F}$. A reasonable estimate for a given temperature can be found using Eq.2.13, where v_{T} is the Saybolt kinematic viscosity at the desired temperature, T is the desired temperature, and $v_{100^{\circ}\mathrm{F}}$ is the Saybolt kinematic viscosity at $100^{\circ}\mathrm{F}$.

$$v_T = v_{100^{\circ}F}\left(1 + \frac{1}{16400}(T - 100)\right) \qquad (2.13)$$

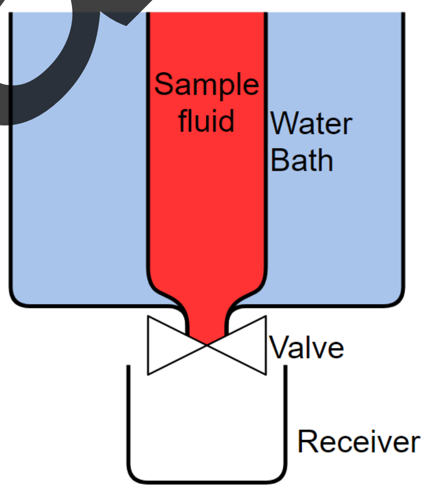

Figure 2.9: Saybolt viscometer

2.2.4.2 Redwood Viscometer

A schematic of the Redwood viscometer is shown in Fig.2.10 below. It bears a striking resemblance to the Saybolt viscometer, with the exception being that the valve is now a ball valve. Once the desired temperature for the sample has been reached, the ball is pulled out of the orifice and the sample fluid flows into the receiver. Again, this viscometer analyses the kinematic viscosity.

The Redwood viscometer also has its own units for viscosity, “redwood seconds”. This is the time it takes for 50 ml to pour into the receiver.

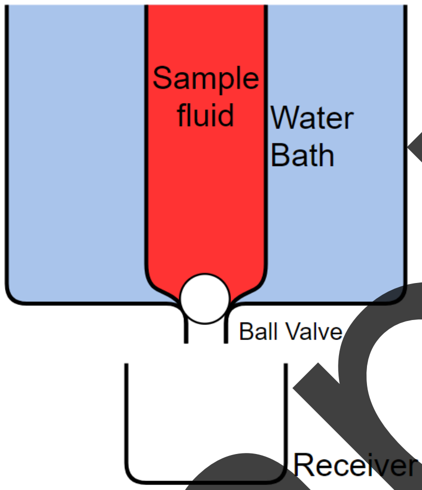

Figure 2.10: Redwood viscometer