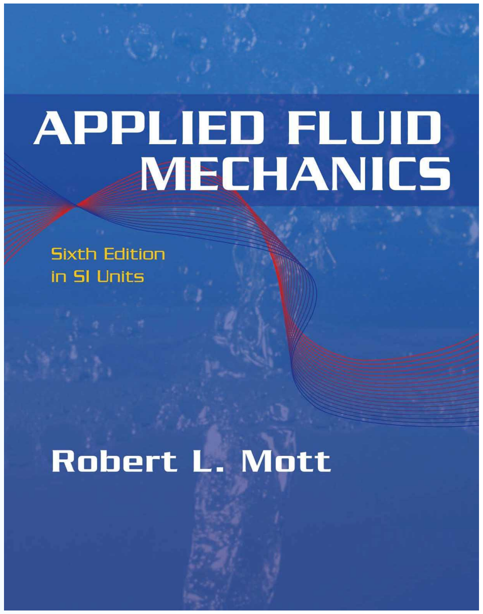
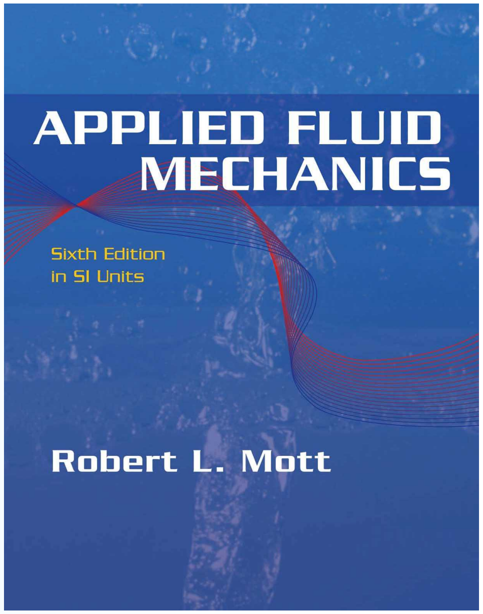
Applied Fluid Mechanics



1. The Nature of Fluid and the Study of Fluid Mechanics
2. Viscosity of Fluid
3. Pressure Measurement
4. Forces Due to Static Fluid
5. Buoyancy and Stability
6. Flow of Fluid and Bernoulli's Equation
7. General Energy Equation
8. Reynolds Number, Laminar Flow, Turbulent Flow and Energy Losses Due to Friction

Applied Fluid Mechanics



9. Velocity Profiles for Circular Sections and Flow in Noncircular Sections
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Applied Fluid Mechanics

17. Drag and Lift
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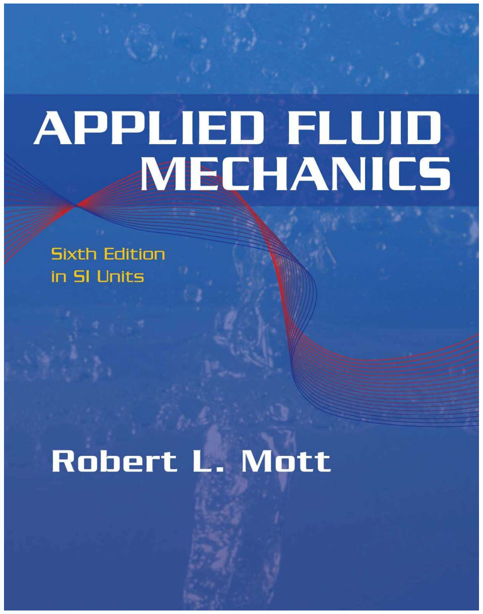


2. Viscosity of Fluids

Chapter Objectives

1. Define *dynamic viscosity*.
2. Define *kinematic viscosity*.
3. Identify the units of viscosity.
4. Describe the difference between a *Newtonian fluid* and a *non-Newtonian fluid*.
5. Describe the methods of viscosity measurement using the *rotating-drum viscometer*, the *capillary-tube viscometer*, the *falling-ball viscometer*, and the *Saybolt Universal viscometer*.
6. Describe the variation of viscosity with temperature for both liquids and gases.
7. Define *viscosity index*.
8. Describe the viscosity of lubricants using the SAE viscosity grades and the ISO viscosity grades.

2. Viscosity of Fluids

Chapter Outline

1. Dynamic Viscosity
2. Kinematic Viscosity
3. Newtonian Fluids and Non-Newtonian Fluids
4. Variation of Viscosity with Temperature
5. Viscosity Measurement
6. SAE Viscosity Grades
7. ISO Viscosity Grades
8. Hydraulic Fluids for Fluid Power Systems

2. Viscosity of Fluids

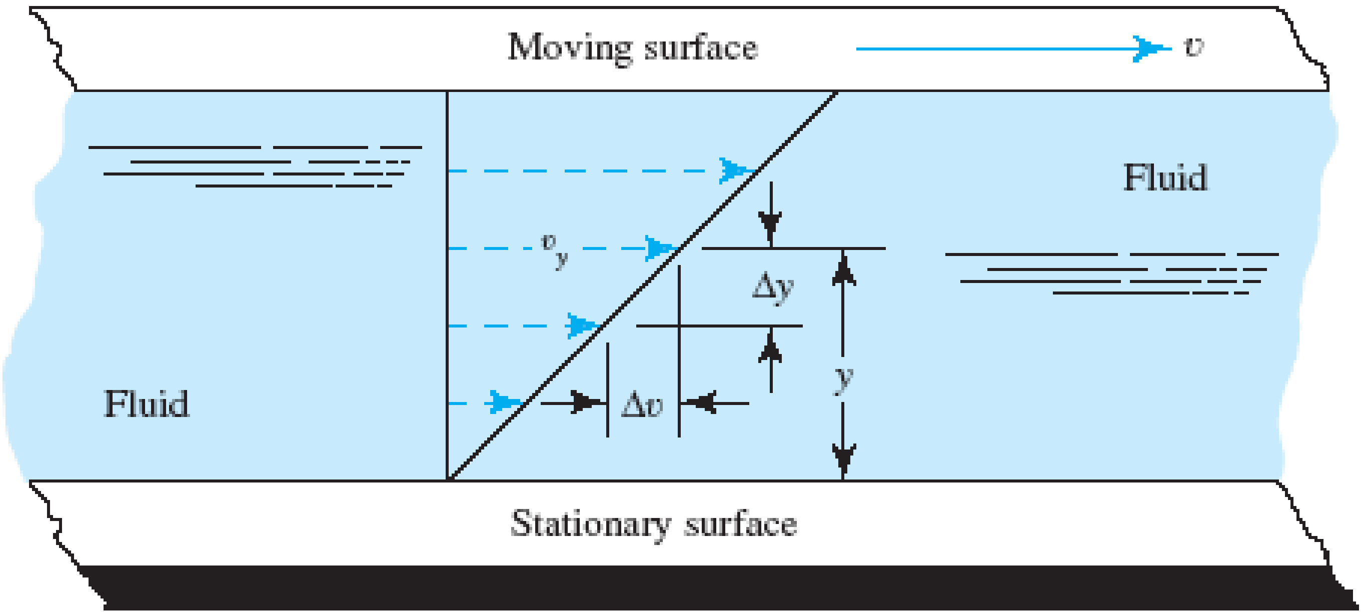
2.1 Dynamic Viscosity

- As a fluid moves, a shear stress is developed in it, the magnitude of which depends on the viscosity of the fluid.
- *Shear stress*, denoted by the Greek letter (tau), τ, can be defined as the force required to slide one unit area layer of a substance over another.
- Thus, τ is a force divided by an area and can be measured in the units of N/m^2 (Pa) or lb/ft^2.

2. Viscosity of Fluids

2.1 Dynamic Viscosity

- Fig 2.1 shows the velocity gradient in a moving fluid.



2. Viscosity of Fluids

2.1 Dynamic Viscosity

- The fact that the shear stress in the fluid is directly proportional to the velocity gradient can be stated mathematically as

$$\tau = \mu(\Delta v/\Delta y) \qquad (2\text{–}1)$$

where the constant of proportionality Â (the Greek letter miu) is called the *dynamic viscosity* of the fluid. The term *absolute viscosity* is sometimes used.

2. Viscosity of Fluids

2.1.1 Unit of Dynamic Viscosity

- The definition of dynamic viscosity can be derived from Eq. (2–1) by solving for µ:

$$\mu = \frac{\tau}{\Delta v / \Delta y} = \tau\left(\frac{\Delta y}{\Delta v}\right) \qquad (2\text{–}2)$$

- The units for ? can be derived by substituting the SI units into Eq. (2–2) as follows:

$$\mu = \frac{\text{N}}{\text{m}^2} \times \frac{\text{m}}{\text{m/s}} = \frac{\text{N}\bullet\text{s}}{\text{m}^2}$$

2. Viscosity of Fluids

2.1.1 Unit of Dynamic Viscosity

- Because Pa is another name for N/m^2, we can also express μ as

$$\mu = \text{Pa}\cdot\text{s}$$

- Because $1N = 1\ kg\cdot m/s^2$ can be expressed as

$$\mu = \text{N} \times \frac{\text{s}}{\text{m}^2} = \frac{\text{kg}\cdot\text{m}}{\text{s}^2} \times \frac{\text{s}}{\text{m}^2} = \frac{\text{kg}}{\text{m}\cdot\text{s}}$$

- Thus $N\cdot m/s^2$, Pa·s or kg/m·s may be used for μ in the SI system.

2. Viscosity of Fluids

2.1.1 Unit of Dynamic Viscosity

- Table 2.1 shows the system conversion.

Unit System	Dynamic Viscosity Units
International System (SI)	$N \cdot s/m^2$, $Pa \cdot s$, or $kg/(m \cdot s)$
U.S. Customary System	$lb \cdot s/ft^2$ or $slug/(ft \cdot s)$
cgs system (obsolete)	poise = $dyne \cdot s/cm^2$ = $g/(cm \cdot s)$ = 0.1 $Pa \cdot s$
	centipoise = poise/100 = 0.001 $Pa \cdot s$ = 1.0 $mPa \cdot s$

2. Viscosity of Fluids

2.2 Kinematic Viscosity

- The kinematic viscosity ν (the Greek letter nu) is defined as

$$\nu = \mu/\rho \qquad (2\text{–}3)$$

- Because μ and ρ are both properties of the fluid, ν is also a property.
- We can derive the SI units for kinematic viscosity by substituting the previously developed units for μ and ρ:

$$\nu = \frac{\mu}{\rho} = \mu\left(\frac{1}{\rho}\right)$$

$$\nu = \frac{\text{kg}}{\text{m}\cdot\text{s}} \times \frac{\text{m}^3}{\text{kg}}$$

$$\nu = \text{m}^2/\text{s}$$

2. Viscosity of Fluids

2.2 Kinematic Viscosity

- Table 2.2 lists the kinematic viscosity units in the three most widely used systems.

Unit System	Kinematic Viscosity Units
International System (SI)	m^2/s
U.S. Customary System	ft^2/s
cgs system (obsolete)	stoke $= cm^2/s = 1 \times 10^{-4}\ m^2/s$
	centistoke $=$ stoke/100 $= 1 \times 10^{-6}\ m^2/s = 1\ mm^2/s$

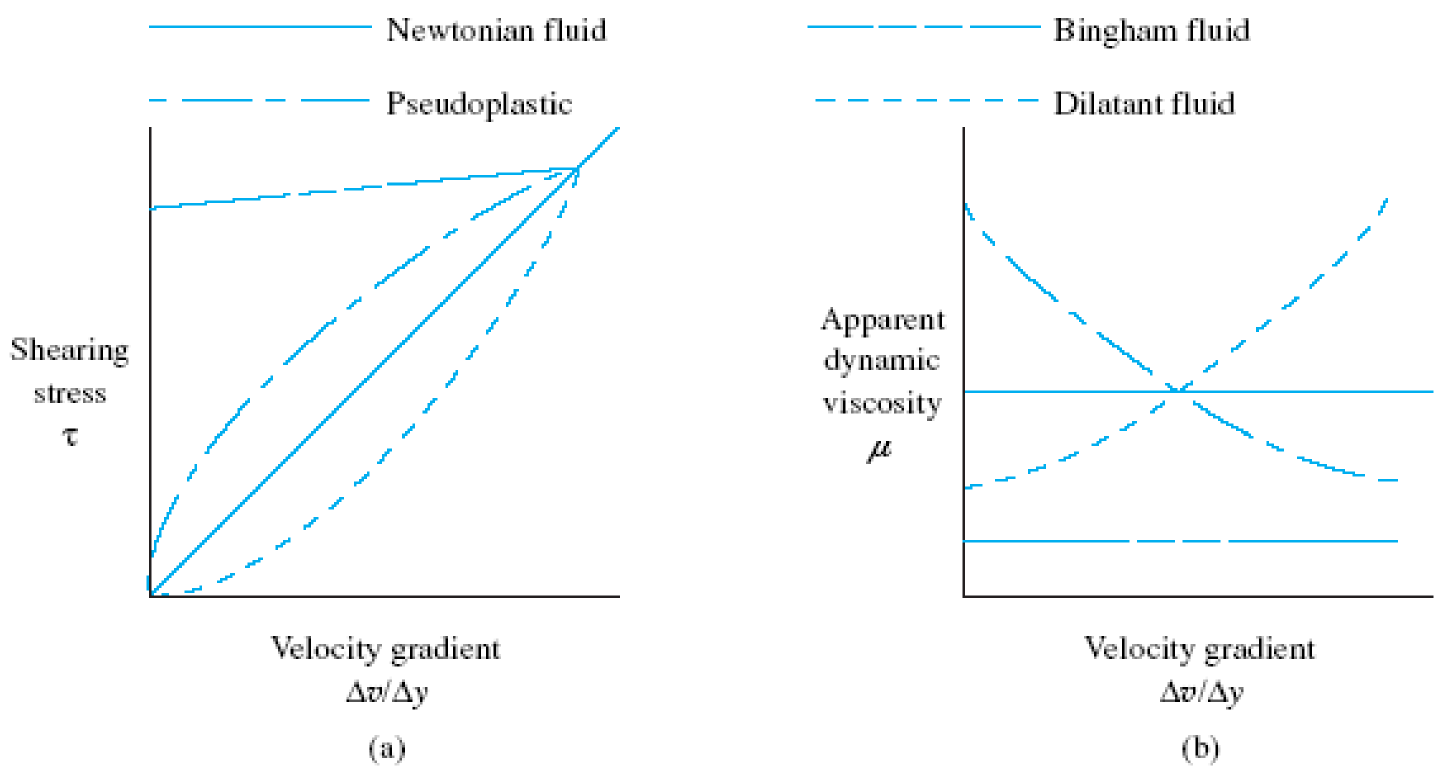
2.3 Newtonian Fluids and Non-Newtonian Fluids

- The study of the deformation and flow characteristics of substances is called *rheology*, which is the field from which we learn about the viscosity of fluids.
- One important distinction is between a *Newtonian fluid* and a *non-Newtonian fluid*.
- Any fluid that behaves in accordance with Eq. (2–1) is called a *Newtonian fluid*.
- Conversely, a fluid that does not behave in accordance with Eq. (2–1) is called a *non-Newtonian fluid*.

2. Viscosity of Fluids

2.3 Newtonian Fluids and Non-Newtonian Fluids

- Fig 2.2 shows the Newtonian and non- Newtonian fluids.



2.3 Newtonian Fluids and Non-Newtonian Fluids

- Two major classifications of non-Newtonian fluids are *time-independent* and *time-dependent* fluids.
- As their name implies, time-independent fluids have a viscosity at any given shear stress that does not vary with time.
- The viscosity of timedependent fluids, however, changes with time.

2. Viscosity of Fluids

2.3 Newtonian Fluids and Non-Newtonian Fluids

- Three types of time-independent fluids can be defined:

1. *Pseudoplastic or Thixotropic* The plot of shear stress versus velocity gradient lies above the straight, constant sloped line for Newtonian fluids, as shown in Fig. 2.2. The curve begins steeply, indicating a high apparent viscosity. Then the slope decreases with increasing velocity gradient.

2. Viscosity of Fluids

2.3 Newtonian Fluids and Non-Newtonian Fluids

2. *Dilatant Fluids* The plot of shear stress versus velocity gradient lies below the straight line for Newtonian fluids. The curve begins with a low slope, indicating a low apparent viscosity. Then, the slope increases with increasing velocity gradient.
3. *Bingham Fluids* Sometimes called *plug-flow fluids*, Bingham fluids require the development of a significant level of shear stress before flow will begin, as illustrated in Fig. 2.2. Once flow starts, there is an essentially linear slope to the curve indicating a constant apparent viscosity.

2. Viscosity of Fluids

2.3.1 Viscosity of Liquid Polymers

- Five additional viscosity factors are typically measured or computed for polymers:

1. *Relative viscosity*
2. *Inherent viscosity*
3. *Reduced viscosity*
4. *Specific viscosity*
5. *Intrinsic viscosity* (also called *limiting viscosity number*)

2.4 Variation of Viscosity with Temperature

- Table 2.3 shows the viscosity for different fluids.

Fluid	Temperature (°C)	Dynamic Viscosity ($N \cdot s/m^2$ or $Pa \cdot s$)
Water	20	1.0×10^{-3}
Gasoline	20	3.1×10^{-4}
SAE 30 oil	20	3.5×10^{-1}
SAE 30 oil	80	1.9×10^{-2}

2.4.1 Viscosity Index

- A fluid with a high viscosity index exhibits a small change in viscosity with temperature. A fluid with a low viscosity index exhibits a large change in viscosity with temperature.
- All kinematic viscosity values are in the unit of mm^2/s:

$$VI = \frac{L - U}{L - H} \times 100 \qquad (2\text{–}4)$$

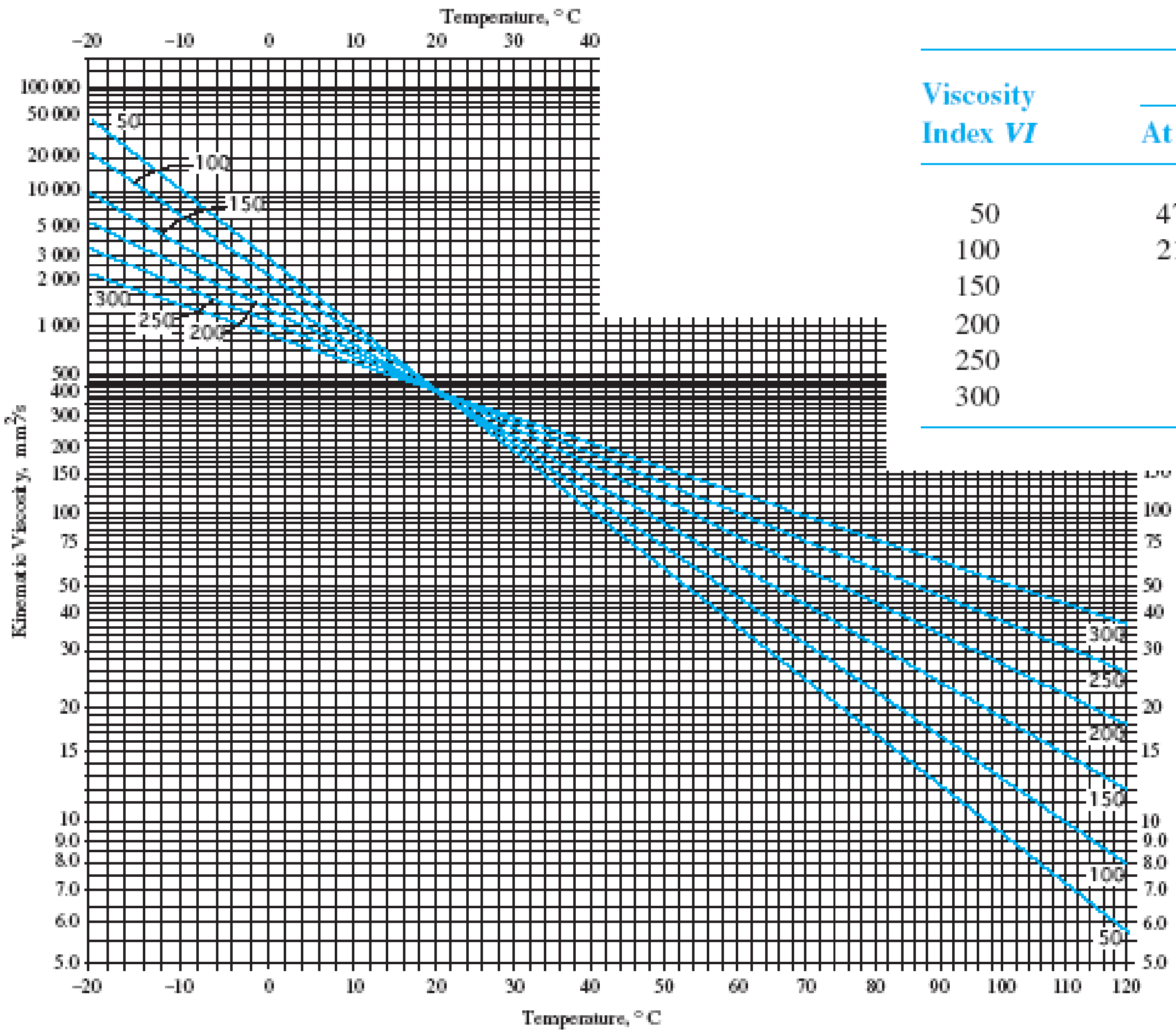
where *U* Kinematic viscosity at of the test oil

L Kinematic viscosity 40°C at of a standard oil of 0 *VI* having the same viscosity at as the test oil 100°C

2. Viscosity of Fluids

2.4.1 Viscosity Index

- Fig 2.3 shows the typical viscosity index curves.



Viscosity Index *VI*	Kinematic Viscosity ν (mm²/s)		
	At −20°C	At 20°C	At 100°C
50	47 900	400	9.11
100	21 572	400	12.6
150	9985	400	18.5
200	5514	400	26.4
250	3378	400	37.1
300	2256	400	51.3

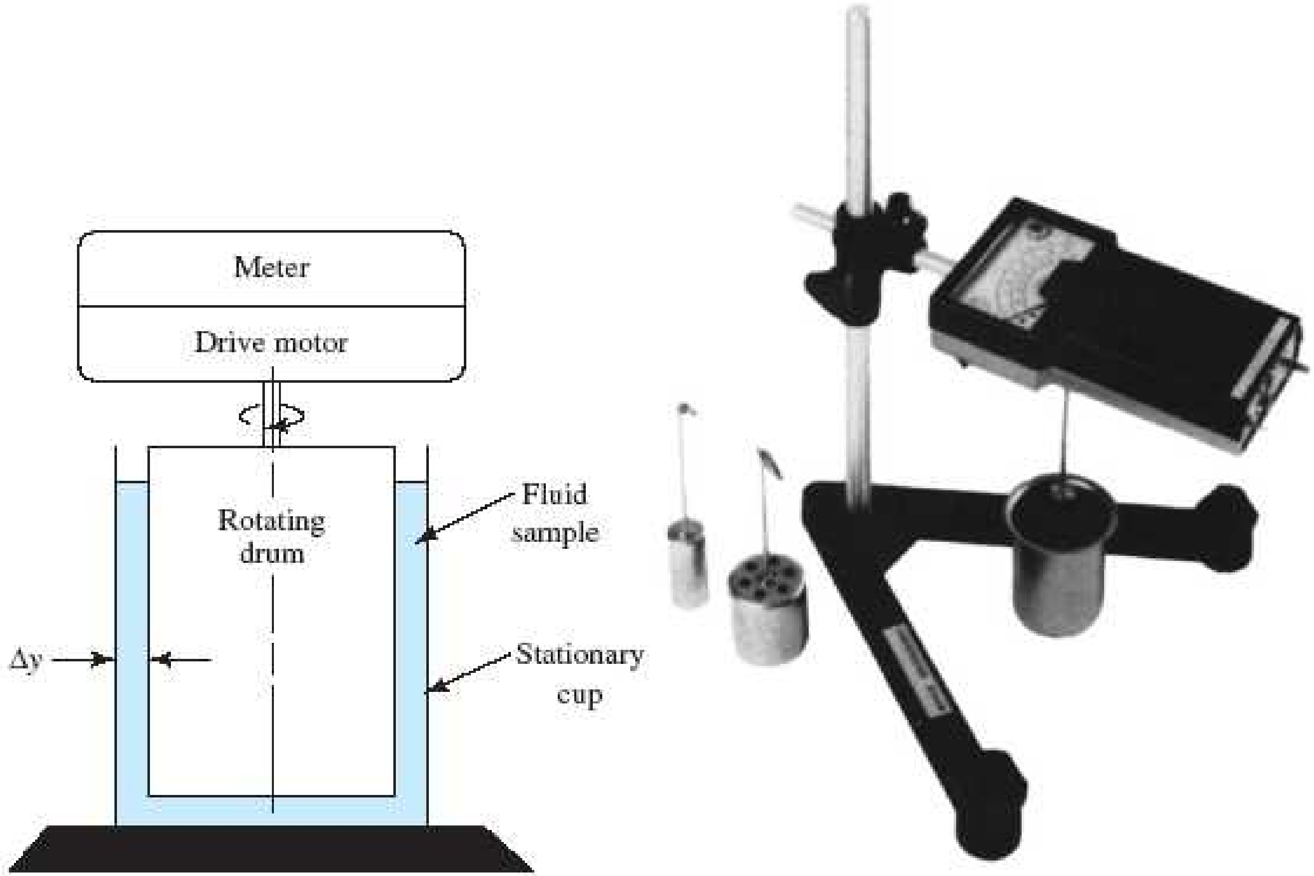
2. Viscosity of Fluids

2.5 Viscosity Measurement

- Devices for characterizing the flow behavior of liquids are called *viscometers* or *rheometers*.
- ASTM International generates standards for viscosity measurement and reporting.

2.5.1 Rotating Drum Viscometer

- Fig 2.4 shows the rotating-drum viscometer.



(a) Sketch of system components (b) Commercially available viscometer

2. Viscosity of Fluids

2.5.1 Rotating Drum Viscometer

- The apparatus shown in Fig. 2.4(a) measures viscosity by the definition of dynamic viscosity given in Eq. (2–2), which we can write in the form

$$\mu = \tau/(\Delta v/\Delta y)$$

- The dynamic viscosity of the fluid can be computed from the simple equation

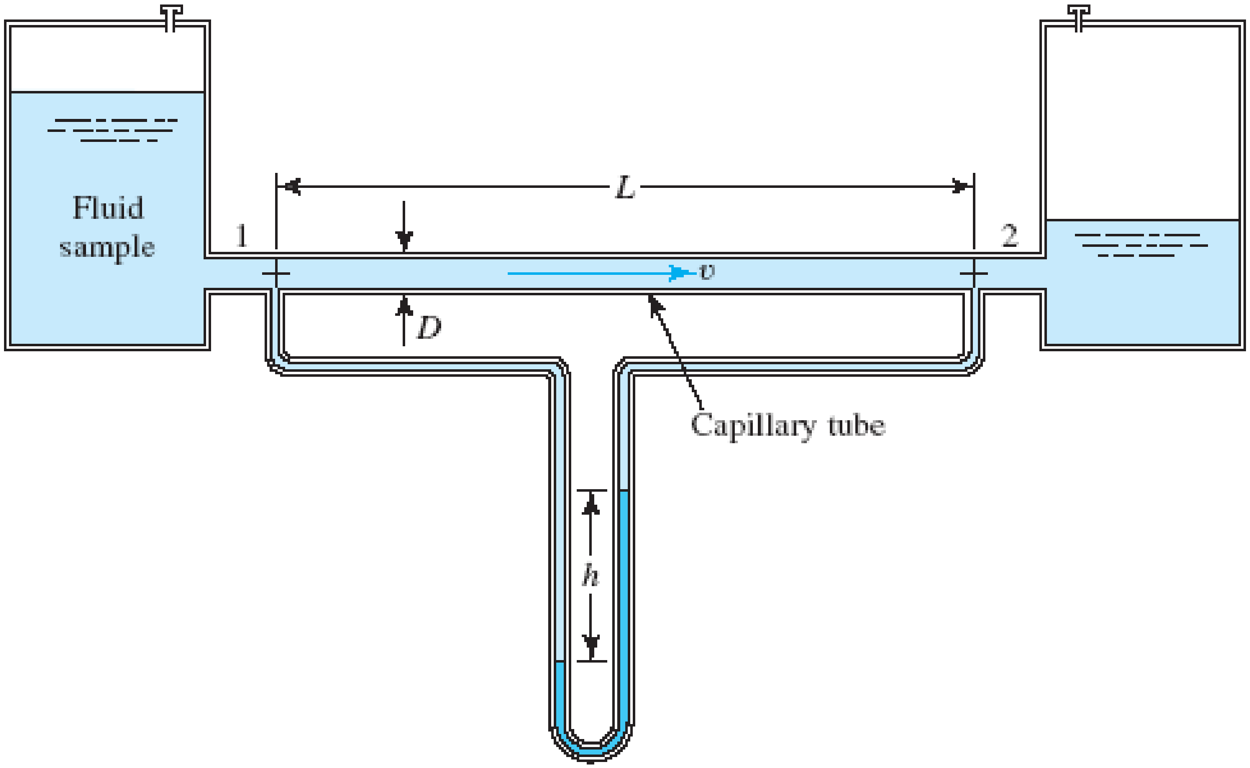
$$\mu = \frac{K}{(n_2/n_1 - 1)}$$

- where n_2 is the speed of the outer tube and n_1 is the speed of the internal rotor. *K* is a calibration constant provided by the instrument manufacturer.

2. Viscosity of Fluids

2.5.2 Capillary Tube Viscometer

- Fig 2.5 shows the Capillary-tube viscometer.



2. Viscosity of Fluids

2.5.2 Capillary Tube Viscometer

- As the fluid flows through the tube with a constant velocity, some energy is lost from the system, causing a pressure drop that can be measured by using manometers.
- The magnitude of the pressure drop is related to the fluid viscosity by the following equation,

$$\mu = \frac{(p_1 - p_2)D^2}{32vL} \qquad (2\text{–}5)$$

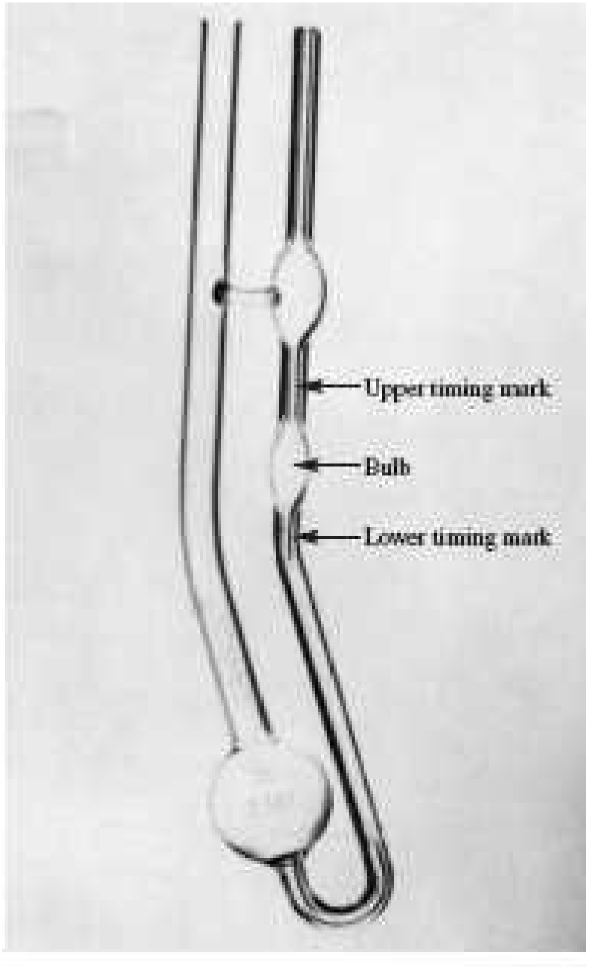
2.5.2 Capillary Tube Viscometer

- In Eq. (2–5), *D* is the inside diameter of the tube, v is the fluid velocity, and *L* is the length of the tube between points 1 and 2 where the pressure is measured.

2. Viscosity of Fluids

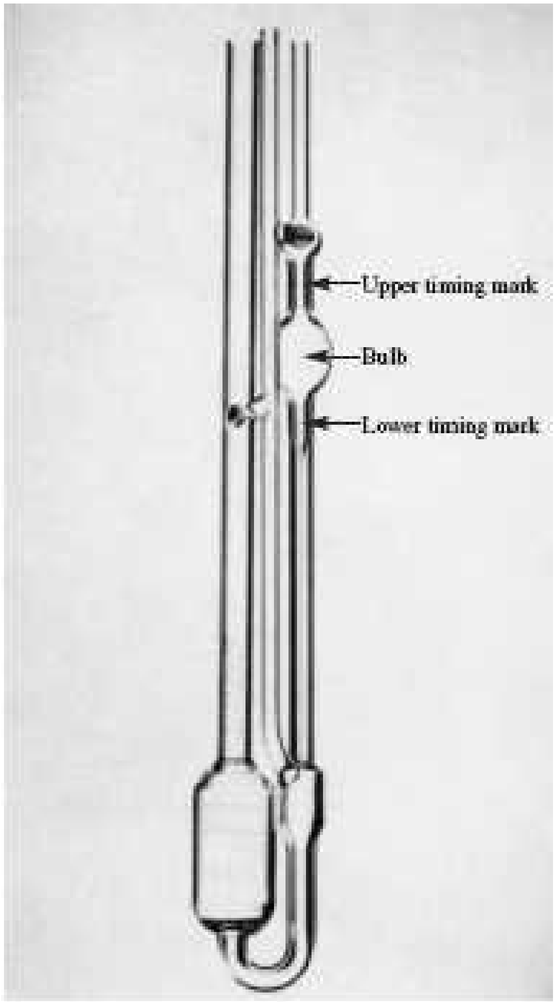
2.5.3 Standard Calibrated Glass Capillary Viscometers

- Fig 2.6 shows the Cannon–Fenske routine viscometer.



2.5.3 Standard Calibrated Glass Capillary Viscometers

- Fig 2.7 shows the Ubbelohde viscometer.



2.5.3 Standard Calibrated Glass Capillary Viscometers

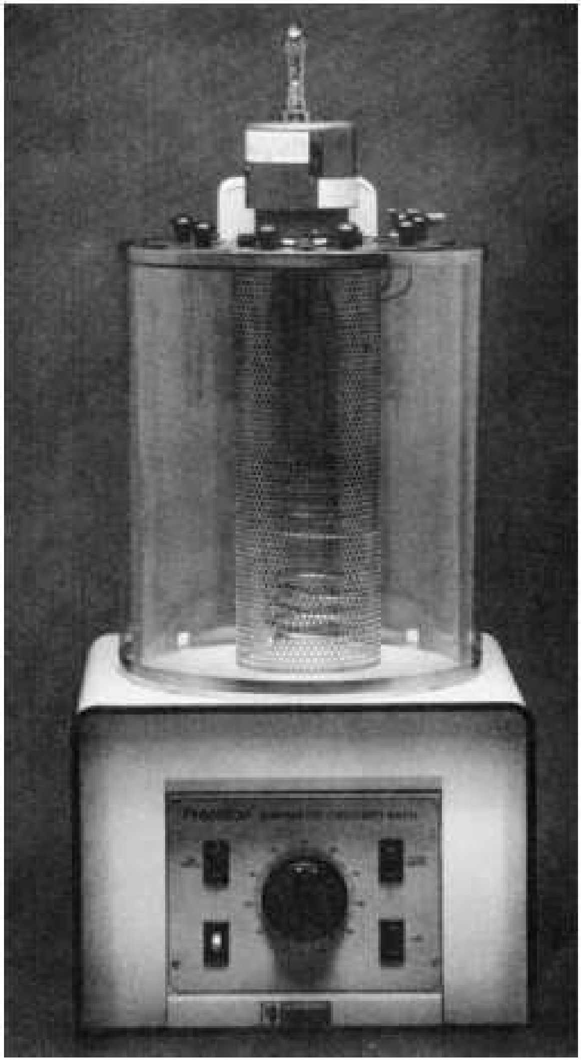
- The kinematic viscosity is computed by multiplying the flow time by the calibration constant of the viscometer supplied by the vendor.
- The viscosity unit used in these tests is the centistoke (cSt), which is equivalent to mm^2/s.

2.5.4 Falling-Ball Viscometer

- As a body falls in a fluid under the influence of gravity only, it will accelerate until the downward force (its weight) is just balanced by the buoyant force and the viscous drag force acting upward.
- Its velocity at that time is called the *terminal velocity*.
- Fig 2.8 shows the kinematic viscosity bath for holding standard calibrated glass capillary viscometers.
- Fig 2.9 shows the falling-ball viscometer.
- Fig 2.10 shows the free-body diagram of a ball in a falling-ball viscometer.

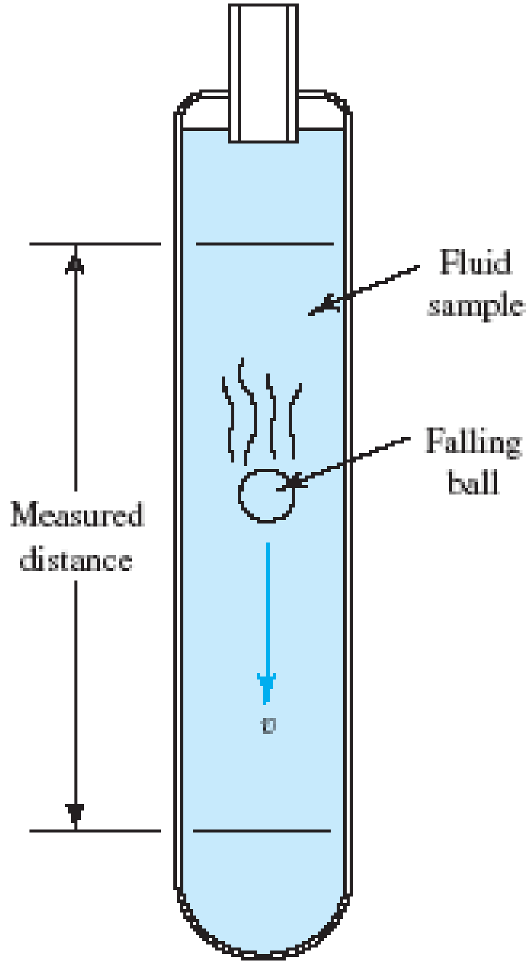
2. Viscosity of Fluids

2.5.4 Falling-Ball Viscometer



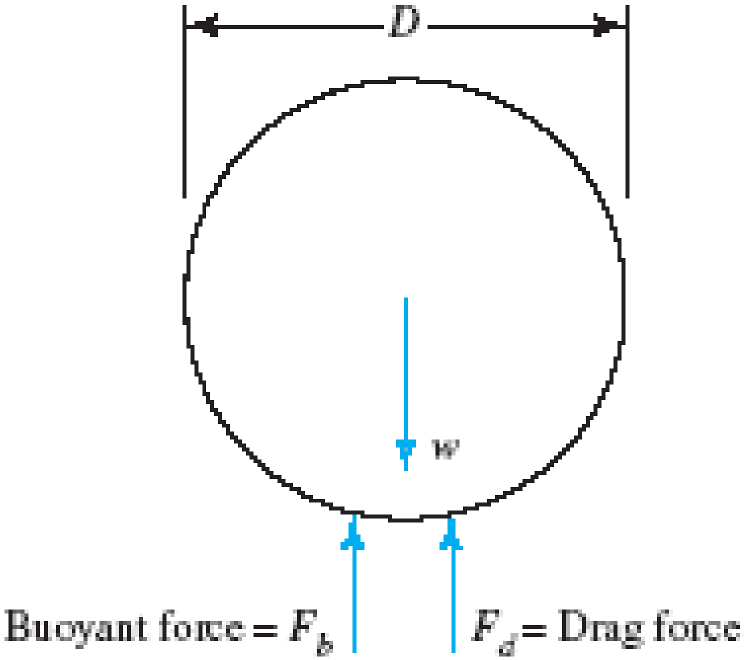
2. Viscosity of Fluids

2.5.4 Falling-Ball Viscometer



2. Viscosity of Fluids

2.5.4 Falling-Ball Viscometer



2. Viscosity of Fluids

2.5.4 Falling-Ball Viscometer

- Figure 2.10 shows a free-body diagram of the ball, where *w* is the weight of the ball, Fb, is the buoyant force, and is the viscous drag force on the ball.
- Therefore, we have

$$w - F_b - F_d = 0. \quad (2\text{–}6)$$

- If γ_s is the specific weight of the sphere, γ_f is the specific weight of the fluid, *V* is the volume of the sphere, and *D* is the diameter of the sphere, we have

$$w = \gamma_s V = \gamma_s \pi D^3/6 \quad (2\text{–}7)$$

$$F_b = \gamma_f V = \gamma_f \pi D^3/6 \quad (2\text{–}8)$$

2.5.4 Falling-Ball Viscometer

- For very viscous fluids and a small velocity, the drag force on the sphere is

$$F_d = 3\pi\mu v D \qquad (2\text{–}9)$$

- Equation (2–6) then becomes

$$\mu = \frac{(\gamma_s - \gamma_f)D^2}{18v} \qquad (2\text{–}10)$$

2. Viscosity of Fluids

2.5.5 Saybolt Universal Viscometer

- The ease with which a fluid flows through a small-diameter orifice is an indication of its viscosity.
- Fig 2.11 shows the Saybolt viscometer.
- Fig 2.12 shows the kinematic viscosity ν in SUS versus v in mm^2/s at 37.8°C (100°F).
- The curve is straight above v = 75 mm^2/s , following the equation

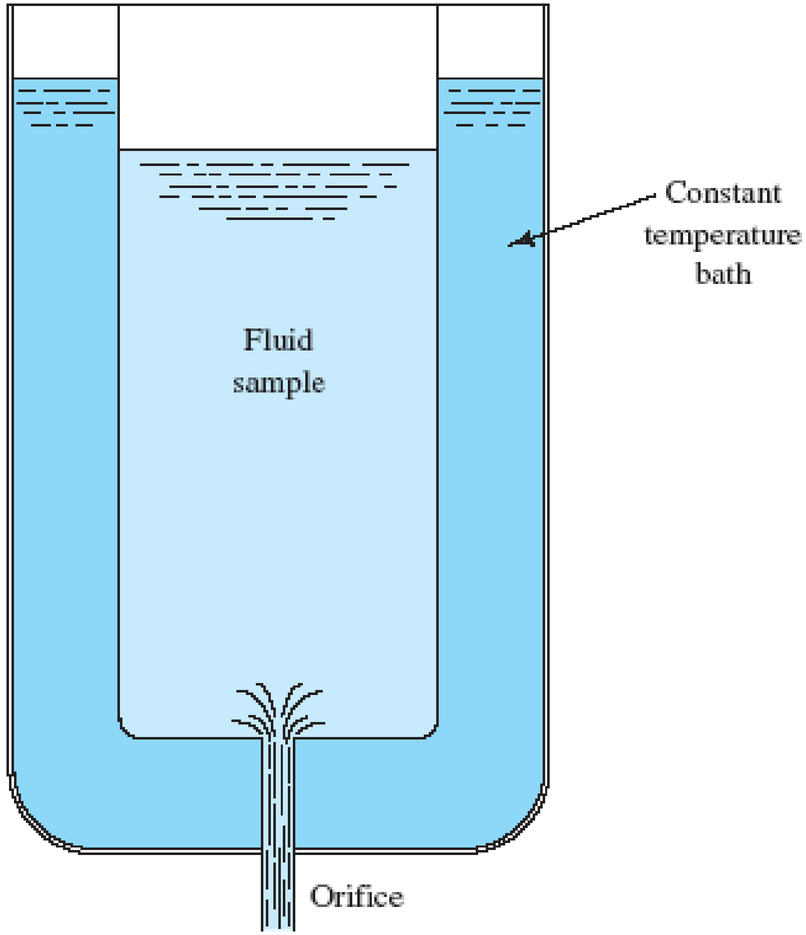
$$\text{SUS} = 4.632\nu \qquad (2\text{–}11)$$

- For a fluid temperature of 100°C (210°F), the equation for the straight-line portion is

$$\text{SUS} = 4.664\nu \qquad (2\text{–}12)$$

2. Viscosity of Fluids

2.5.5 Saybolt Universal Viscometer



(a)

2. Viscosity of Fluids

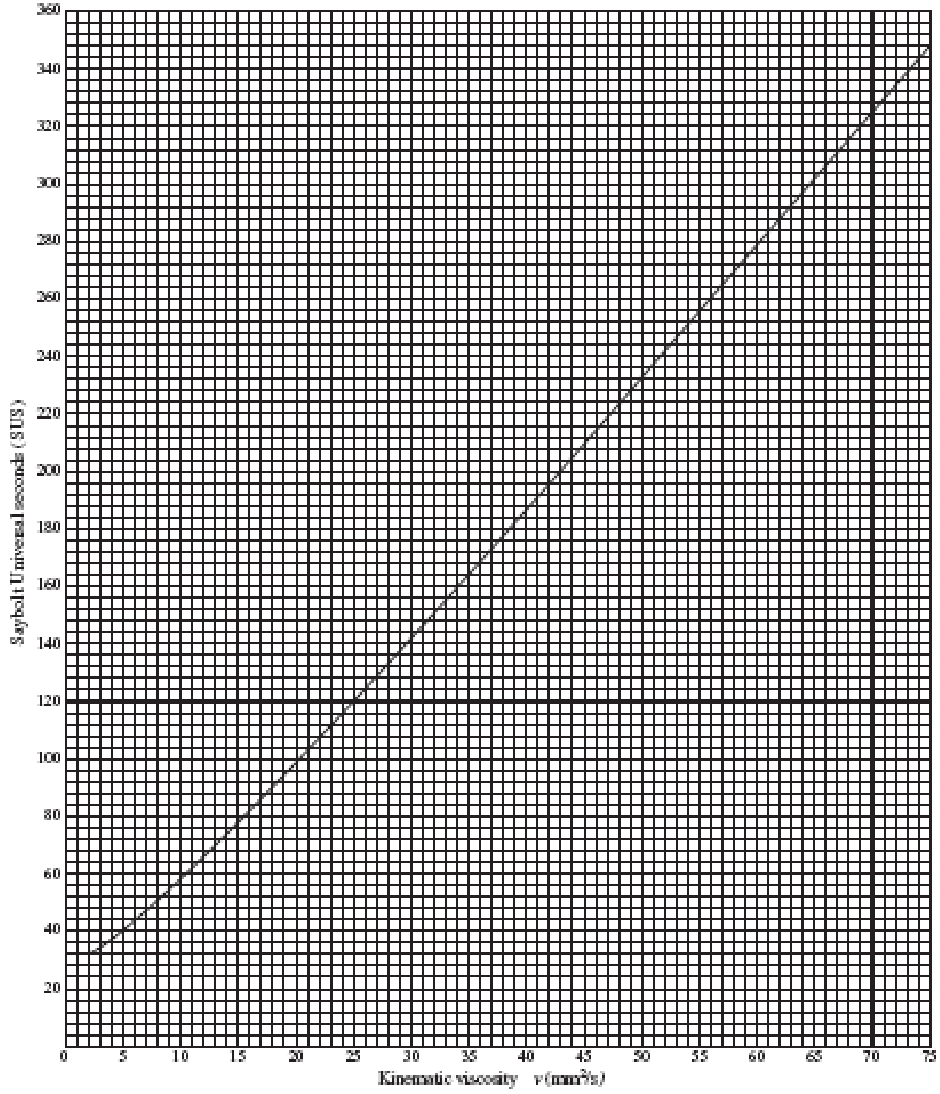
2.5.5 Saybolt Universal Viscometer

(b) Universal Saybolt viscometer

(c) 60 mL flask for collecting Saybolt sample

2. Viscosity of Fluids

2.5.5 Saybolt Universal Viscometer



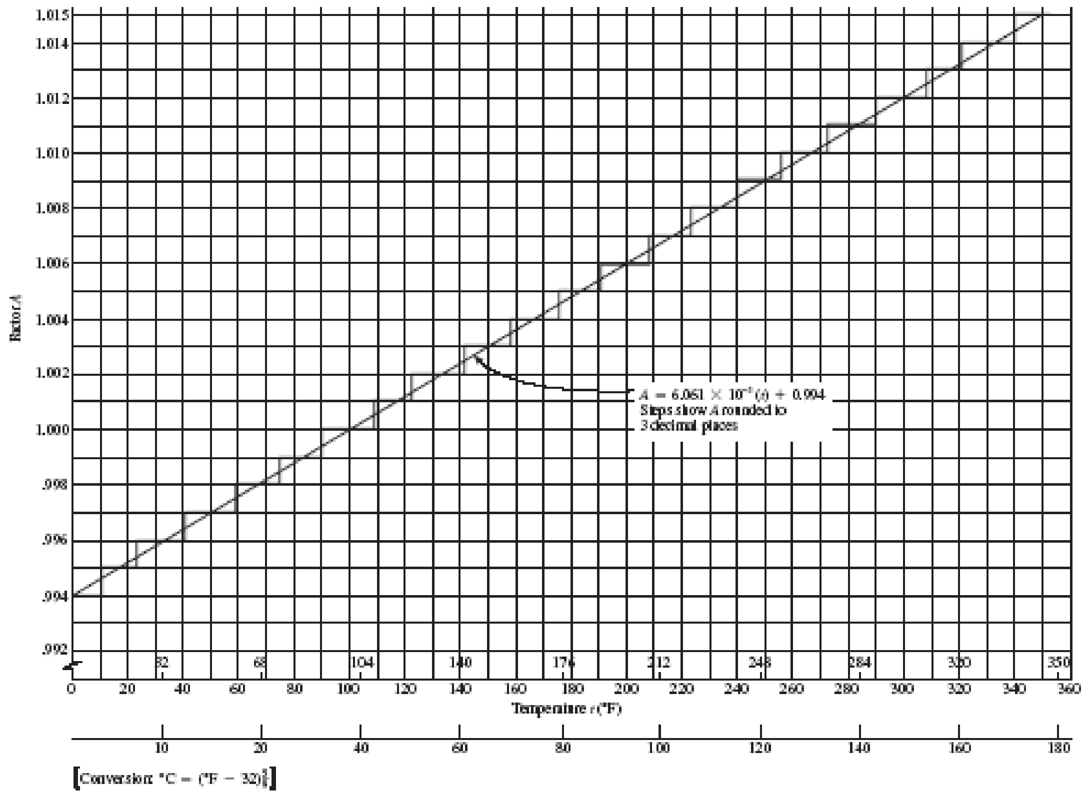
2.3 Newtonian Fluids and Non-Newtonian Fluids

2. *Dilatant Fluids* The plot of shear stress versus velocity gradient lies below the straight line for Newtonian fluids. The curve begins with a low slope, indicating a low apparent viscosity. Then, the slope increases with increasing velocity gradient.
3. *Bingham Fluids* Sometimes called *plug-flow fluids*, Bingham fluids require the development of a significant level of shear stress before flow will begin, as illustrated in Fig. 2.2. Once flow starts, there is an essentially linear slope to the curve indicating a constant apparent viscosity.

2. Viscosity of Fluids

2.5.5 Saybolt Universal Viscometer

- Fig 2.13 shows the factor *A* versus temperature *t* in degrees Fahrenheit used to determine the kinematic viscosity in SUS for any temperature.



2. Viscosity of Fluids

Example 2.2

Given that a fluid at 37.8°C has a kinematic viscosity of 220 mm^2/s, determine the equivalent SUS value at 37.8°C.

Because v > 75 mm^2/s, use Eq. (2–11): SUS = 4.632n = 4.632(220) = 1019 SUS

2. Viscosity of Fluids

Example 2.3

Given that a fluid at 126.7°C (260°F) has a kinematic viscosity of 145 mm^2/s, determine its kinematic viscosity in SUS at 126.7°C.

Example 2.3

Use Eq. (2–13) to compute the factor *A*:

$$A = 6.061 \times 10^{-5}t + 0.994 = 6.061 \times 10^{-5}(260) + 0.994 = 1.010$$

Now find the kinematic viscosity at 37.8°C (100°F) using Eq. (2–11):

$$\text{SUS} = 4.632\nu = 4.632(145) = 671.6\ \text{SUS}$$

Finally, multiply this value by *A* to get the SUS value at 126.7°C (260°F):

$$\text{SUS} = A(671.6) = 1.010(671.6) = 678\ \text{SUS}$$

2.6 SAE Viscosity Grade

- SAE International has developed a rating system for engine oils (Table 2.4) and automotive gear lubricants (Table 2.5) which indicates the viscosity of the oils at specified temperatures.

2. Viscosity of Fluids

2.6 SAE Viscosity Grade

SAE Viscosity Grade	Low Temperature—Dynamic Viscosity: Cranking Condition* (cP) Max. at (°C)	Low Temperature—Dynamic Viscosity: Pumping Condition# (cP) Max. at (°C)	High-Temperature Kinematic Viscosity at 100°C (cSt)+: Min.	High-Temperature Kinematic Viscosity at 100°C (cSt)+: Max.	High-Temperature, High-Shear-Rate Dynamic Viscosity◇ at 150°C (cP) Min.
0W	6200 at −35	60 000 at −40	3.8	—	—
5W	6600 at −30	60 000 at −35	3.8	—	—
10W	7000 at −25	60 000 at −30	4.1	—	—
15W	7000 at −20	60 000 at −25	5.6	—	—
20W	9500 at −15	60 000 at −20	5.6	—	—
25W	13 000 at −10	60 000 at −15	9.3	—	—
20	—	—	5.6	<9.3	2.6
30	—	—	9.3	<12.5	2.9
40	—	—	12.5	<16.3	2.9⊥
40	—	—	12.5	<16.3	3.7⌈
50	—	—	16.3	<21.9	3.7
60	—	—	21.9	<26.1	3.7

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Note: 1 cP = 1 mPa·s ; 1 cSt = 1 mm^2/s

* Using ASTM Standard D 5293

\# Using ASTM D 4684

\+ Using ASTM D 445

◇ Using ASTM D 4683, D 4741, or D 5481

⊥ When used in these multiviscosity grades: 0W-40, 5W-40, 10W-40

⌈ When used in single-grade SAE 40 and in these multiviscosity grades: 15W-40, 20W-40, 25W-40

2. Viscosity of Fluids

2.6 SAE Viscosity Grade

SAE Viscosity Grade	Maximum Temperature for Dynamic Viscosity of 150 000 cP* (°C)	Kinematic Viscosity at 100°C (cSt)#	
		Min.	Max.
70W	−55	4.1	—
75W	−40	4.1	—
80W	−26	7.0	—
85W	−12	11.0	—
80	—	7.0	<11.0
85	—	11.0	<13.5
90	—	13.5	<24.0
140	—	24.0	<41.0
250	—	41.0	—

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Note: 1 cP = 1 mPa·s; 1 cSt = 1 mm^2/s

* Using ASTM D 2983

\# Using ASTM D 445

2. Viscosity of Fluids

2.7 ISO Viscosity Grade

- The standard designation includes the prefix ISO VG followed by a number representing the nominal kinematic viscosity in cSt for a temperature of 40°C.
- Table 2.6 gives the data.

Grade ISO VG	Kinematic Viscosity at 40°C (cSt) or (mm^2/s)		
	Nominal	Minimum	Maximum
2	2.2	1.98	2.40
3	3.2	2.88	3.52
5	4.6	4.14	5.06
7	6.8	6.12	7.48
10	10	9.00	11.0
15	15	13.5	16.5
22	22	19.8	24.2
32	32	28.8	35.2
46	46	41.4	50.6
68	68	61.2	74.8
100	100	90.0	110
150	150	135	165
220	220	198	242
320	320	288	352
460	460	414	506
680	680	612	748
1000	1000	900	1100
1500	1500	1350	1650
2200	2200	1980	2420
3200	3200	2880	3520

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2. Viscosity of Fluids

2.8 Hydraulic Fluid for Fluid Power System

- Fluid power systems use fluids under pressure to actuate linear or rotary devices used in construction equipment, industrial automation systems, agricultural equipment, aircraft hydraulic systems, automotive braking systems, and many others.
- There are several types of hydraulic fluids in common use, including

1. Petroleum oils
2. Water–glycol fluids
3. High water-based fluids (HWBF)
4. Silicone fluids
5. Synthetic oils

2. Viscosity of Fluids

2.8 Hydraulic Fluid for Fluid Power System

- The primary characteristics of such fluids for operation in fluid power systems are

1. Adequate viscosity for the purpose
2. High lubricating capability, sometimes called lubricity
3. Cleanliness
4. Chemical stability at operating temperatures
5. Noncorrosiveness with the materials used in fluid power systems
6. Inability to support bacteria growth
7. Ecologically acceptable
8. High bulk modulus (low compressibility)