Engineering Fluid Mechanics 12th edition Elger Solutions Manual

SKU: 9781119596219-SOLUTIONS

2.1: PROBLEM DEFINITION

Situation:

If the density, ρ, of air increases by a factor of 1.4x due to a temperature change,

a. specific weight increases by 1.4x

b. specific weight increases by 13.7x

c. specific weight remains the same

SOLUTION

Since specific weight is the product ρg, if ρ increases by a factor of 1.4, then specific weight increases by 1.4 times as well. The answer is (a).

Problem 2.2

(T/F) If the temperature of a fluid increases, then the viscosity decreases (i.e., if $T \uparrow$ for a fluid, then $\mu \downarrow$).

Feedback

Claim: The best choice is F

Reasoning: Fig. A.2 shows that the statement is true for liquids but false for gases.

2.3: PROBLEM DEFINITION

Situation:

Oxygen at 50 °F and 100 °F.

Find:

Ratio of viscosities: $\frac{\mu_{100}}{\mu_{50}}$.

SOLUTION

Because the viscosity of gases increases with temperature $\mu_{100}/\mu_{50} > 1$. Correct choice is $\boxed{\text{(c)}}$.

Problem 2.4

A cube will hold 14e3 N of a liquid that has a specific gravity of 0.8.

What is the length in meters of one side of the cube?
(a) 0.67 (b) 1.21 (c) 1.03 (d) 0.81 (e) 1.61

Feedback

Claim: The best choice is (b).

Reasoning:

① $W = \gamma \forall$

$\boxed{?}$

$W = S\gamma_{H_2O}\, a^3$

② $\therefore a = \left(W/S\gamma_{H_2O}\right)^{1/3}$

③ $= \left(\frac{14000\ \text{N}}{0.8}\ \Big|\ \frac{\text{m}^3}{9810\ \text{N}}\right)^{1/3}$

Table F.6

$= 1.2128\ \text{m}$

The steps are

1. Apply the definition of specific weight
2. Build an equation for the goal
3. Calculate the length of the side

Problem 2.5

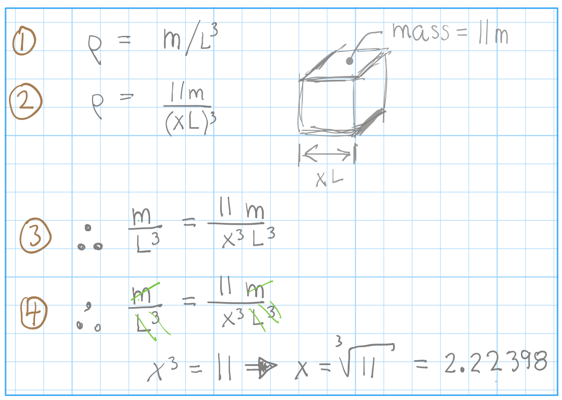
A fluid tank in the shape of a cube holds a mass m of a liquid. Each side of the tank has a length L. What length is required to hold 11 times as much mass of the same liquid, also in a cube shaped tank?

(a) $1.14L$ (b) $2.22L$ (c) $3.67L$ (d) $4.91L$ (e) $2.83L$

Feedback

Claim: The best choice is (b)

Reasoning:



The steps are

1. Apply the definition of density to the small cube
2. Apply the definition of density to the large cube
3. Combine Eqs. (1) and (2)
4. Solve for the length multiplier x

Problem 2.6

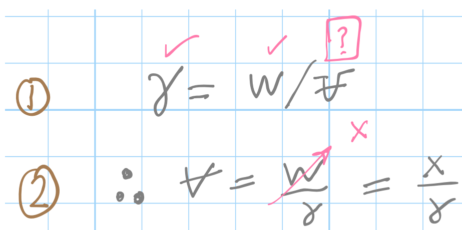
A tank holds $x = 12\,\text{kN}$ of a liquid. What formula gives the volume of the tank?

a. γ/x
b. x/γ
c. γx
d. $1/(\gamma x)$
e. $x\gamma/\rho$

Feedback

Claim: The best choice is (b)

Reasoning:



The steps are:

1. Apply the definition of specific weight
2. Solve for volume

2.7: PROBLEM DEFINITION

Situation:

What are SG, γ, and ρ for mercury?

State you answers in SI units and in traditional units.

SOLUTION

From table A.4 (EFM12e)

	SI	Traditional
SG	13.55	13.55
γ	133,000 $\mathrm{N/m^3}$	847 $\mathrm{lbf/ft^3}$
ρ	13,550 $\mathrm{kg/m^3}$	26.3 $\mathrm{slug/ft^3}$

Problem 2.8

An experiment was performed to measure the bulk modulus of elasticity of a liquid. The pressure was changed from 7 MPa to 14 MPa. The volume changed from 10 L to 9.9 L.

The bulk modulus in MPa is:
(a) 1100 (b) 900 (c) 700 (d) 1000 (e) 1300

Feedback

Claim: The best choice is (c)

Reasoning:

$\boxed{?}$

1. $E_v = -\dfrac{\Delta p \, \forall}{\Delta \forall}$ 1 Eq / 1 Uk $\Rightarrow$ ∴ cracked

2. $= -(14-7)\ \text{MPa} \; \dfrac{10\ \cancel{L}}{(9.9-10)\ \cancel{L}}$

$= 700\ \text{MPa}$

The steps are:
1. Apply the definition of bulk modulus
2. Do the calcs

.

2.9: PROBLEM DEFINITION

Situation:

Liquid fresh water is subjected to an increase in pressure.

Find:

Pressure increase needed to reduce volume by 3%.

Properties:

From Table A.5 (EFM12e), $E = 2.2 \times 10^9$ Pa.

PLAN

Use modulus of elasticity equation to calculate pressure change required to achieve the desired volume change.

SOLUTION

Modulus of elasticity equation

$$\begin{aligned} E &= -\Delta p \frac{\forall}{\Delta \forall} \\ \Delta p &= E \frac{\Delta \forall}{\forall} \\ &= -\left(2.2 \times 10^9 \text{ Pa}\right) \left(\frac{-0.03 \times \forall}{\forall}\right) \\ &= \left(2.2 \times 10^9 \text{ Pa}\right)(0.03) \\ &= 6.6 \times 10^7 \text{ Pa} \end{aligned}$$

$$\boxed{\Delta p = 66 \text{ MPa}}$$

2.10: PROBLEM DEFINITION

Situation:
The term dV/dy, the velocity gradient
a. has dimensions of L/T
b. has dimensions of T^{-1}

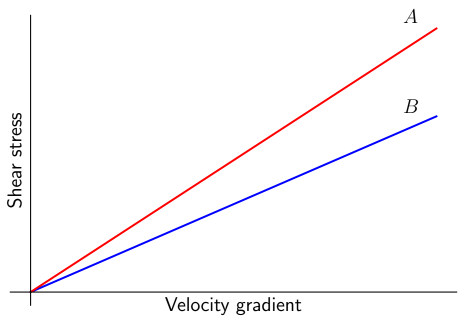
SOLUTION

$$\left[\frac{dV}{dy}\right] = \frac{L}{T} \times \frac{1}{L} = \frac{1}{T}$$
$$\left[\frac{dV}{dy}\right] = T^{-1}$$

Therefore the answer is $\boxed{\text{(b); } \frac{dV}{dy} \text{ has dimensions of } T^{-1}}$

Problem 2.11

(T/F) The viscosity of fluid A is greater than the viscosity of fluid B.



Feedback

True. The reasoning is:

1. The equation $\tau = \mu \frac{dV}{dy}$ matches the slope-intercept equation ($y = mx + b$), with the slope equal to μ and an intercept of 0.
2. Slope $A >$ Slope B
3. Thus $\mu_A > \mu_B$

2.12: PROBLEM DEFINITION

Situation:
Common Newtonian fluids are:

a. toothpaste, catsup, and paint
b. water, oil and mercury
c. all of the above

SOLUTION

The answer is (b). Toothpaste, catsup, and paint are not Newtonian, but are shear-thinning; see Fig. 2.14 in EFM12e.

2.13: PROBLEM DEFINITION

Situation:

SAE 10W30 motor oil is used as a lubricant between two machine parts.

Assume Couette flow.

$\mu = 1 \times 10^{-4}\,\mathrm{lbf} \cdot \mathrm{s/\,ft^2}$

$dV = 4\,\mathrm{ft/\,s}$

$\tau_{\max} = 2\,\mathrm{lbf/\,ft^2}$

Find:

What is the required spacing, in inches?

PLAN

Use the definition of visosity, $\tau = \mu \frac{dV}{dy}$, where dy is the required spacing.

SOLUTION

Find dy

$$\begin{aligned} dy &= \frac{\mu \cdot dV}{\tau} \\ &= \left(\frac{1 \times 10^{-4}\,\mathrm{lbf} \cdot \mathrm{s}}{\mathrm{ft}^2}\right)\left(\frac{4\,\mathrm{ft}}{\mathrm{s}}\right)\left(\frac{\mathrm{ft}^2}{2\,\mathrm{lbf}}\right) \\ &= (2 \times 10^{-4}\,\mathrm{ft})\left(\frac{12\,\mathrm{in}}{1\,\mathrm{ft}}\right) \\ & \boxed{dy = 2.4 \times 10^{-3}\,\mathrm{in}} \end{aligned}$$

The spacing needs to be equal to, or wider than 2.4×10^{-3} in in order for the shear stress to be less than 2 $\mathrm{lbf/\ ft^2}$.

2.14: PROBLEM DEFINITION

Situation:

Velocity distribution of crude oil between two walls.

$\mu = 8 \times 10^{-5}\,\text{lbf s/ ft}^2$, $B = 0.1\,\text{ft}$.

$u = 100y(0.1 - y)\,\text{ft/ s}$, $T = 100\,^\circ\text{F}$.

Find:

Shear stress at walls.

SOLUTION

Velocity distribution

$$u = 100y(0.1 - y) = 10y - 100y^2$$

dV/dy = derivative of the equation for velocity

$$\begin{aligned} du/dy &= 10 - 200y \\ (du/dy)_{y=0} &= 10\ \text{s}^{-1} \ \text{ and } \ (du/dy)_{y=0.1} = -10\ \text{s}^{-1} \end{aligned}$$

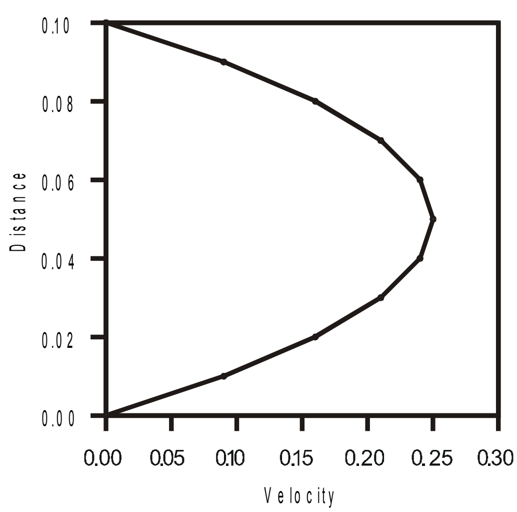
Shear stress

$$\tau_0 = \mu\frac{du}{dy} = (8 \times 10^{-5}) \times 10$$

$$\boxed{\tau_0 = 8{\times}10^{-4}\ \text{lbf/ft}^2}$$

$$\boxed{\tau_{0.1} = 8{\times}10^{-4}\ \text{lbf/ft}^2}$$

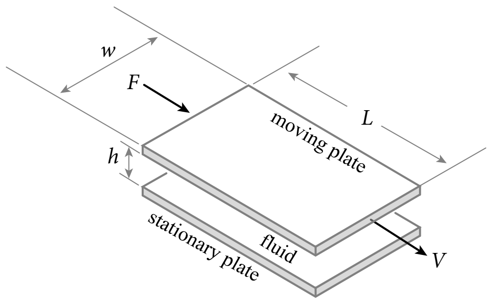
Plot, where distance is in ft, and velocity is in ft/s.



Problem 2.15

This sliding plate viscometer is being calibrated with water at room conditions. The parameters are: $h = 0.8\,\text{mm}$, $L = 30\,\text{cm}$, $w = 10\,\text{cm}$, and $V = 4\,\text{m/s}$.

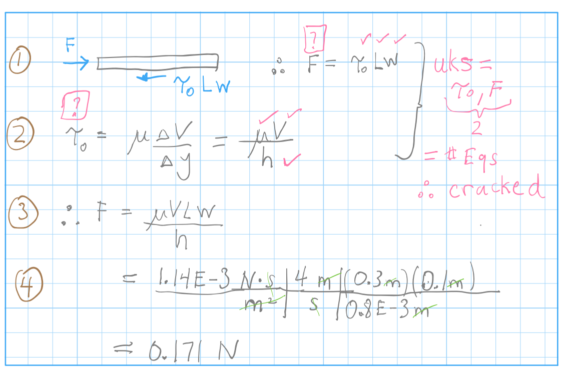
In mN, the force that will be measured is:
(a) 360 (b) 170 (c) 280 (d) 410 (e) 90



Feedback

Claim: The best choice is (b)

Reasoning: The flow in a viscometer is usually modeled as a Couette flow. Thus, the solution can be found like this:



The steps are:

1. Draw a FBD. Apply $\Sigma F_x = 0$.
2. Apply the viscosity equation to a Couette flow
3. Build an equation for the goal
4. Do the calcs

$\boxed{\text{2.16: PROBLEM DEFINITION}}$

Situation:
A hemispherical drop of water is suspended under a surface

Find:
Diameter of droplet just before separation

Properties:
Table A.5 (EFM12e) (20 °C): $\gamma = 9790\,\text{N/m}^3, \sigma = 0.073\,\text{N/m}$.

$\boxed{\text{SOLUTION}}$

Equilibrium

$$
\begin{aligned}
\text{Weight of droplet} &= \text{Force due to surface tension} \\
\left(\frac{\pi D^3}{12}\right)\gamma &= (\pi D)\,\sigma
\end{aligned}
$$

Solve for D

$$
\begin{aligned}
D^2 &= \frac{12\sigma}{\gamma} \\
&= \frac{12 \times (0.073\text{ N/m})}{9790\text{ N/m}^3} = 8.948 \times 10^{-5}\,\text{m}^2 \\
D &= 9.459 \times 10^{-3}\,\text{m}
\end{aligned}
$$

$$\boxed{D = 9.46\,\text{mm}}$$

2.17: PROBLEM DEFINITION

Find:

How does vapor pressure change with increasing temperature?

a. it increases

b. it decreases

c. it stays the same

SOLUTION

The answer is (a).

REVIEW

Vapor pressure increases with increasing temperature. To get an everyday feel for this, note from the Appendix that the vapor pressure of water at 212 °F (100 °C) is 101 kPa (14.7 psia). To get water to boil at a lower temperature, you would have to exert a vacuum on the water. To keep it from boiling until a higher temperature, you would have to pressurize it.

Problem 2.1

Define a **system** using the standard structure of a definition.

Feedback

Feedback. An example follows.

A **system** is the **body or region** that is selected by the problem solver and analyzed for the purpose of solving the problem effectively.

Problem 2.2

For the situation described in the frame, answer the following questions:

a. What system would an engineer select?
b. What is state 1 (the initial state)?
c. What is state 2 (the final state)?
d. List three examples of properties at state 1?
e. List three examples of properties at state 2?
f. List two examples of problem parameters that are not properties?

Situation
During a study of drag, an engineer wishes to calculate how far a tennis ball will travel. The tennis ball is launched at a speed of 55 m/s, and an angle of 20° with respect to a horizontal axis. When the ball is launched, it is 1.5 m above the ground. The model will include the effects of air drag.

Feedback

Feedback:

a. the tennis ball
b. the initial state describes the tennis ball at the instant it is launched
c. the final state describes the tennis ball at the instant just before it hits the ground
d. The initial speed is $V = 55$ m/s. The mass of the tennis ball is $= 58$ g. The launch angle is $\theta = 20°$
e. The mass of the tennis ball is $m = 58$ g; The tennis ball diameter is $D = 6.5$ cm, The final height is $h = 0$ m
f. the work done by air on the tennis ball; the drag force

Problem 2.3

For each item in this list, give a simple, one-sentence definition: (a) system (b) state (c) property

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Feedback

Feedback: The definitions should be similar to the following:

a. A *system* is the item (component, system, volume, etc.) that the engineer selects for analysis.
b. The *state* refers to the conditions of the system as specified by the values of its properties.
c. A *property* is an attribute of a system (e.g., mass, energy, temperature, density, weight, and height) that depend only on the present conditions of the system.

2.4: PROBLEM DEFINITION

Find:

Where in this text can you find:

a. density data for such liquids as oil and mercury?

b. specific weight data for air (at standard atmospheric pressure) at different temperatures?

c. specific gravity data for sea water and kerosene?

SOLUTION

a. Density data for liquids other than water can be found in Table A.4 in EFM12e. Temperatures are specified.

b. Data for several properties of air (at standard atmospheric pressure) at different temperatures are in Table A.3 in EFM12e.

c. Specific gravity and other data for liquids other than water can be found in Table A.4 in EFM12e. Temperatures are specified.

2.5: PROBLEM DEFINITION

Situation:

Regarding water and seawater:

a. Which is more dense, seawater or freshwater?

b. Find (SI units) the density of seawater (10°C, 3.3% salinity).

c. Find the same in traditional units.

d. What pressure is specified for the values in (b) and (c)?

SOLUTION

a. Seawater is more dense, because of the weight of the dissolved salt.

b. The density of seawater (10°C, 3.3% salinity) in SI units is 1026 kg/m^3, see Table A.3 in EFM12e.

c. The density of seawater (10°C, 3.3% salinity) in traditional units is 1.99 $slugs/ft^3$, see Table A.3 in EFM12e.

d. The specified pressure for the values in (b) and (c) is standard atmospheric pressure; as stated in the title of Table A.3 in EFM12e.

2.6: PROBLEM DEFINITION

Situation:

Where in this text can you find:

a. values of surface tension (σ) for kerosene and mercury?

b. values for the vapor pressure (p_v) of water as a function of temperature?

SOLUTION

a. Table A.4 (EFM12e). Note that these values of surface tension assume a liquid/air interface.

b. Table A.5 (EFM12e). Note that vapor pressure tables are always in absolute pressure; since p_v is a material property, it can't be documented for gage pressures because gage pressures vary from day to day, and from place to place.

$\boxed{\text{2.7: PROBLEM DEFINITION}}$

Situation:

Open tank of water.
$T_{20} = 20\,^\circ\text{C}$, $T_{80} = 80\,^\circ\text{C}$.
$\forall = 500$ L, $d = 2\,\text{m}$.

Find:

Percentage change in volume.
Water level rise for given diameter.

Properties:

From Table A.5 (EFM12e): $\rho_{20} = 998\frac{\text{kg}}{\text{m}^3}$,and $\rho_{80} = 972\frac{\text{kg}}{\text{m}^3}$.

$\boxed{\text{PLAN}}$

Density changes as a function of temperature. For a given system (mass = constant):

a. Find the mass for a known density and volume
b. Use geometry to get water level change

$\boxed{\text{SOLUTION}}$

a. Calculate percentage change in volume for this mass of water at two temperatures.
For the first temperature, the volume is given as $\forall_{20} = 500$ L $= 0.5\,\text{m}^3$.Its density is $\rho_{20} = 998\frac{\text{kg}}{\text{m}^3}$. Therefore, the mass for both cases is given by.

$$\begin{aligned} m &= 998\frac{\text{kg}}{\text{m}^3} \times 0.5\,\text{m}^3 \\ &= 499.0\,\text{kg} \end{aligned}$$

For the second temperature, that mass takes up a larger volume:

$$\begin{aligned} \forall_{80} &= \frac{m}{\rho} = \frac{499.0\,\text{kg}}{972\frac{\text{kg}}{\text{m}^3}} \\ &= 0.513\,\text{m}^3 \end{aligned}$$

Therefore, the percentage change in volume is

$$\begin{aligned} \frac{0.513\,\text{m}^3 - 0.5\,\text{m}^3}{0.5\,\text{m}^3} &= 0.0267 \\ &\text{volume \% change}\boxed{= 2.7\%} \end{aligned}$$

b. If the tank has $D = 2\,\text{m}$, then $\forall = \pi r^2 h = 3.14h$.Therefore:

$$\begin{aligned} h_{20} &= 0.159\,\text{m} \\ h_{80} &= 0.163\,\text{m} \end{aligned}$$

$$\boxed{\text{water level rise is } 0.163 - 0.159\,\text{m} = 0.004257\,\text{m} = 4.26\,\text{mm}}$$

REVIEW

Density changes can result from temperature changes, as well as pressure changes.

Problem 2.8

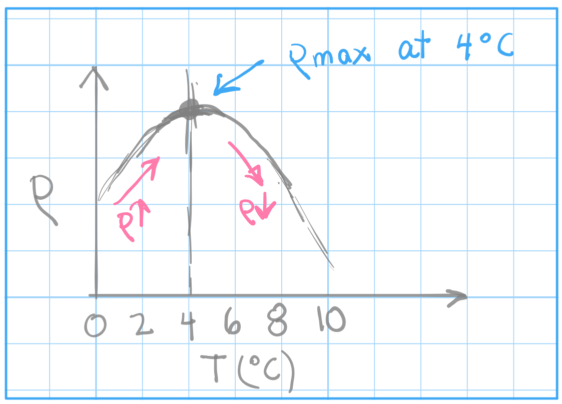
Consider liquid water at atmospheric pressure over a temperature ranging from freezing to boiling.

(T/F) If $T \uparrow$, then $\rho \downarrow$.

Feedback

Claim: The best choice is F

Reasoning: As shown in the sketch that follows, If $T < 4\,°\text{C}$ and $T \uparrow$, then $\rho \uparrow$. For more information, see **bit.ly/water_physics**.



Tip: The fact that water at p_{atm} has a maximum density at $4\,°\text{C}$ is noted in Table 2.1. However, this fact is not evident in Table A.5 because density values are only given for selected temperatures.

Problem 2.9

(T/F) The density of water at 4 °C and 1 bar is greater than the density of water at 1 °C and 1 bar.

Feedback

Claim: The best choice is T

Reasoning: At 1 bar, the density of liquid water is maximum at 4 °C; see the notes in Table 2.1.

Problem 2.10

(T/F) At atmospheric pressure, a liter of water at 100 °C will weigh about 0.4 N less than a liter of water at 5 °C.

Feedback

Claim: The best choice is T

Reasoning:

$$\left.\begin{aligned}\gamma_{5^\circ C} &\cong 9.8\ \mathrm{N/L}\\ \gamma_{100^\circ C} &\cong 9.4\ \mathrm{N/L}\end{aligned}\right\}\ \text{Table A.5}$$

$$\Delta\gamma = 0.4\ \mathrm{N/L}$$

2.11: PROBLEM DEFINITION

Situation:
The following questions relate to viscosity.

Find:
(a) The primary dimensions of viscosity and five common units of viscosity.
(b) The viscosity of motor oil (in traditional units).

SOLUTION

a) Primary dimensions of viscosity are $\boxed{\left[\frac{M}{LT}\right]}$.
Five common units are:

$$\boxed{\text{i) } \frac{\text{N}\cdot\text{s}}{\text{m}^2};\ \text{ ii) } \frac{\text{dyn}\cdot\text{s}}{\text{cm}^2};\ \text{ iii) poise; iv) centipoise; and v) } \frac{\text{lbf}\cdot\text{s}}{\text{ft}^2}}$$

(b) To find the viscosity of SAE 10W-30 motor oil at 115 °F, there are no tabular data in the text. Therefore, one should use Figure A.2 (EFM12e). For traditional units (because the temperature is given in Farenheit) one uses the left-hand axis to report that $\boxed{\mu = 1.2 \times 10^{-3}\,\frac{\text{lbf}\cdot\text{s}}{\text{ft}^2}}$.
Note: one should be careful to identify the correct factor of 10 for the log cycle that contains the correct data point. For example, in this problem, the answer is between 1×10^{-3} and 1×10^{-2}. Therefore the answer is 1.2×10^{-3} and not 1×10^{-2}.

Problem 2.12

(T/F) If the pressure of water increases, then the viscosity will also increase.

Feedback

Claim. False is the best answer. Reasoning: The viscosity of a liquid or a gas for typical conditions is independent of pressure.

Problem 2.13

Consider the following units:

I. $\text{Pa} \cdot \text{s}$
II. $\text{lbf} \cdot \text{s}/\text{ft}^2$
III. $\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$
IV. $\text{lbm}/\text{ft} \cdot \text{s}$
V. stoke

Which choices are absolute viscosity units?
(a) All (b) I and II (c) All except V (d) V only (e) I and V

Feedback

Claim: The best choice is (c)

Reasoning:

1. Common units for viscosity—aka, absolute viscosity—are listed in Table F.1
2. Table F.1 shows that items I through IV are viscosity units
3. Table F.1 shows that item V is a kinematic viscosity unit

Problem 2.14

(T/F) If you have a fluid and if $\nu \downarrow$ as $T \uparrow$, then the fluid must be a liquid.

Feedback

Claim: The best choice is T.

Reasoning: Fig. A.3 shows that

- Liquids: if $T \uparrow$, then $\nu \downarrow$
- Gases: if $T \uparrow$, then $\nu \uparrow$

2.15: PROBLEM DEFINITION

Situation:
When looking up values for density, absolute viscosity, and kinematic viscosity, which statement is most true for BOTH liquids and gases?

a. all 3 of these properties vary with temperature
b. all 3 of these properties vary with pressure
c. all 3 of these properties vary with temperature and pressure

SOLUTION

Best answer is (a). The absolute viscosities of liquids and gases do not vary with pressure.
Answer (c) is also acceptable, because kinematic viscosity does vary with pressure (because density does).

2.16: PROBLEM DEFINITION

Situation:

Kinematic viscosity (select all that apply)

a. is another name for absolute viscosity

b. is viscosity/density

c. is dimensionless because forces are canceled out

d. has dimensions of L^2/T

SOLUTION

The answers are (b) and (d).

Problem 2.17

What is the kinematic viscosity of air in units of m^2/s at typical room conditions?

(a) 15e-5 (b) 18e-5 (c) 18e-6 (d) 15e-6 (e) 29e-5

Feedback

The best choice is (d).

The reasoning is:
1. Typical room conditions are about $20\,^{\circ}\mathrm{C}$ and $1.0\,\mathrm{atm}$
2. At these conditions, Table F.4 indicates that
   $\nu\ = 1.51 \times 10^{-5}\,\mathrm{m}^2/\mathrm{s}$

Problem 2.18

(T/F) At room conditions, the kinematic viscosity of air is greater than the kinematic viscosity of water.

Feedback

Claim: The best choice is T

Reasoning:

1. Air (Table F.4): $\nu = 15.1 \times 10^{-6}\,\mathrm{m^2/s}$
2. Water (Table F.5): $\nu = 1.14 \times 10^{-6}\,\mathrm{m^2/s}$
3. Thus, $\nu(\mathrm{air}) > \nu(\mathrm{water})$

Problem 2.19

(T/F) At room conditions, the dynamic viscosity of air is greater than the dynamic viscosity of water.

Feedback

Claim: The best choice is F

1. Air (Table F.4): $\mu = 18.1\,\mu\text{Pa}\cdot\text{s}$
2. Water (Table F.5): $\mu = 1140\,\mu\text{Pa}\cdot\text{s}$
3. Thus, $\mu(\text{air}) \ll \mu(\text{water})$

2.20: PROBLEM DEFINITION

Situation:

Change in viscosity and density due to temperature.
$T_1 = 10\,°\mathrm{C}$, $T_2 = 90\,°\mathrm{C}$.
$p_{atm} = 101\,\mathrm{kN/\,m^2}$ (standard atmospheric pressure)

Find:

Change in viscosity and density of water.
Change in viscosity and density of air.

Properties:

See Plan, below.

PLAN

Use tabular data; use subtraction to calculate changes in property values.
For water, use data from Table A.5 (EFM12e). For air, use data from Table A.3 (EFM12e).

SOLUTION

Changes in viscosity and density of water

$$\mu_{90} = 3.15 \times 10^{-4}\ \ \mathrm{N \cdot s/\,m^2}$$
$$\mu_{10} = 1.31 \times 10^{-3}\ \ \mathrm{N{\cdot}s/\,m^2}$$
$$\boxed{\Delta\mu = -9.95 \times 10^{-4}\ \ \mathrm{N{\cdot}s/\,m^2}}$$

$$\rho_{90} = 965\ \mathrm{kg/m^3}$$
$$\rho_{10} = 1000\ \mathrm{kg/m^3}$$
$$\boxed{\Delta\rho = -35\ \ \mathrm{kg/\,m^3}}$$

Changes in viscosity and density of air

$$\mu_{90} = 2.13 \times 10^{-5}\ \mathrm{N \cdot s/m^2}$$
$$\mu_{10} = 1.76 \times 10^{-5}\ \mathrm{N \cdot s/m^2}$$
$$\boxed{\Delta\mu = 3.70 \times 10^{-6}\,\mathrm{N \cdot s/\,m^2}}$$

$$\rho_{90} = 0.97\ \mathrm{kg/m^3}$$
$$\rho_{10} = 1.25\ \mathrm{kg/m^3}$$
$$\boxed{\Delta\rho = -0.28\ \mathrm{kg/\,m^3}}$$

Problem 2.21

The temperature of liquid water decreases from 80 °C to 20 °C. The percent change in absolute viscosity is

(a) 6 (b) 183 (c) 132 (d) 92 (e) 78

Feedback

Claim: The best choice is (b)

Reasoning:

1 $\% \text{ Change} = \dfrac{(\text{new} - \text{original})}{(\text{original})} 100$ Table A.5

2 new: $\mu_{H_2O}(T = 20°C) = 1E{-3}\ Pa \cdot s$

original: $\mu_{H_2O}(T = 80°C) = 3.54E{-4}\ Pa \cdot s$

3 $\therefore\ \% \text{ Change} = \left(\dfrac{10 - 3.54}{3.54}\right) 100$

$= 182.4\%$

The steps are

1. Apply the formula for % change
2. Look up values of viscosity
3. Do the calcs

2.22: PROBLEM DEFINITION

Situation:

Air at certain temperatures.

$T_1 = 10\,^\circ\text{C}$, $T_2 = 50\,^\circ\text{C}$.

Find:

Change in kinematic viscosity.

Properties:

From Table A.3 (EFM12e), $\nu_{50} = 1.79 \times 10^{-5}$ m^2/s, $\nu_{10} = 1.41 \times 10^{-5}$ m^2/s.

PLAN

Use properties found in Table A.3 (EFM12e).

SOLUTION

$$\begin{aligned} \Delta v_{\text{air},10\to 50} &= (1.79 - 1.41) \times 10^{-5} \\ & \boxed{\Delta \text{v}_{\text{air},10\to 50} = 3.8 \times 10^{-6} \text{m}^2/\text{s}} \end{aligned}$$

2.23: PROBLEM DEFINITION

Situation:

Viscosity of SAE 10W-30 oil, kerosene and water.
$T = 50\,^{\circ}\mathrm{C}$

Find:

Dynamic and kinematic viscosity of each fluid.

PLAN

Use property data found in Fig. A.2, Fig. A.2, and Table A.5 (all in EFM12e).

SOLUTION

	Oil (SAE 10W-30)		kerosene		water	
$\mu(\mathrm{N \cdot s/m^2})$	$\boxed{4.0\times10^{-2}}$	(Fig. A-2)	$\boxed{1.0\times10^{-3}}$	(Fig. A-2)	$\boxed{5.47\times10^{-4}}$	Table A.5
$\nu(\mathrm{m^2/s})$	$\boxed{4.5\times10^{-5}}$	(Fig. A-3)	$\boxed{1.5\times10^{-6}}$	(Fig. A-3)	$\boxed{5.53\times10^{-7}}$	Table A.5

Note to instructor:
Expect only accuracy to 1 significant figure on the oil and kerosene data, because of difficulty interpolating on a log-scale figure. Students should, however, be able to report the correct order of magnitude (power of 10) for the 2 forms of viscosity for these 2 fluids.

2.24: PROBLEM DEFINITION

Situation:

Comparing properties of air and water at standard atmospheric pressure

Find:

Ratio of dynamic viscosity of air to that of water.

Ratio of kinematic viscosity of air to that of water.

Properties:

Air (20 °C, 1 atm), Table A.3 (EFM12e), $\mu = 1.81 \times 10^{-5}$ N·s/m^2; $\nu = 1.51 \times 10^{-5}$ m^2/s

Water (20 °C, 1 atm), Table A.5 (EFM12e), $\mu = 1.00 \times 10^{-3}$ N·s/m^2; $\nu = 1.00 \times 10^{-6}$ m^2/s

SOLUTION

Dynamic viscosity

$$\frac{\mu_{\text{air}}}{\mu_{\text{water}}} = \frac{1.81 \times 10^{-5}\,\text{N} \cdot \text{s/ m}^2}{1.00 \times 10^{-3}\,\text{N} \cdot \text{s/ m}^2}$$

$$\boxed{\frac{\mu_{\text{air}}}{\mu_{\text{water}}} = 1.81 \times 10^{-2}}$$

Kinematic viscosity

$$\frac{\nu_{\text{air}}}{\nu_{\text{water}}} = \frac{1.51 \times 10^{-5}\,\text{m}^2/\,\text{s}}{1.00 \times 10^{-6}\,\text{m}^2/\,\text{s}}$$

$$\boxed{\frac{\nu_{\text{air}}}{\nu_{\text{water}}} = 15.1}$$

REVIEW

1. Water at these conditions (liquid) is about 55 times more viscous than air (gas).

2. However, the corresponding kinematic viscosity of air is 15 times higher than the kinematic viscosity of water. The reason is that kinematic viscosity includes density and $\rho_{\text{air}} \ll \rho_{\text{water}}$.

3. Remember that

   (a) kinematic viscosity (ν) is related to dynamic viscosity (μ) by: $\nu = \mu/\rho$.

   (b) the labels "viscosity," "dynamic viscosity," and "absolute viscosity" are synonyms.

2.25: PROBLEM DEFINITION

Situation:

Properties of air and water.
$T = 40\,°\text{C}$, $p = 170\,\text{kPa}$.

Find:

Kinematic and dynamic viscosities of air and water.

Properties:

Air data from Table A.3 (EFM12e), $\mu_{\text{air}} = 1.91 \times 10^{-5}$ N·s/m^2
Water data from Table A.5 (EFM12e), $\mu_{\text{water}} = 6.53 \times 10^{-4}$ N·s/m^2, $\rho_{\text{water}} = 992$ kg/m^3.

PLAN

Apply the ideal gas law to find density. Find kinematic viscosity as the ratio of dynamic and absolute viscosity.

SOLUTION

A.) Air
Ideal gas law

$$\begin{aligned}\rho_{\text{air}} &= \frac{p}{RT} \\ &= \frac{170,000\,\text{Pa}}{(287\,\text{J/ kg K})\,(313.2\,\text{K})} \\ &= 1.89\ \text{kg/m}^3\end{aligned}$$

$$\boxed{\mu_{\text{air}} = 1.91 \times 10^{-5}\ \frac{\text{N}\cdot\text{s}}{\text{m}^2}}$$

$$\begin{aligned}\nu &= \frac{\mu}{\rho} \\ &= \frac{1.91 \times 10^{-5}\,\text{N s/ m}^2}{1.89\,\text{kg/ m}^3}\end{aligned}$$

$$\boxed{\nu_{\text{air}} = 10.1 \times 10^{-5}\,\text{m}^2/\,\text{s}}$$

B.) water

$$\boxed{\mu_{\text{water}} = 6.53 \times 10^{-5}\ \text{N}\cdot\text{s/m}^2}$$

$$\begin{aligned}\nu &= \frac{\mu}{\rho} \\ \nu &= \frac{6.53 \times 10^{-4}\,\text{N s/ m}^2}{992\,\text{kg/ m}^3}\end{aligned}$$

$$\boxed{\nu_{\text{water}} = 6.58 \times 10^{-7}\ \text{m}^2/\text{s}}$$

Problem 2.26

(T/F) Specific gravity is defined as the density of a material divided by the density of water when the water is in the liquid state at 4 °C.

Feedback

Claim: The best choice is T.

Reasoning: In this text, this is the definition. Some resources use a different reference temperature.

Problem 2.27

What is the specific weight of nitrogen in units of newtons per cubic meter at a temperature of −10 °C and a pressure of 0.6 bar gage?

(a) 20 (b) 31 (c) 36 (d) 24 (e) 39

Feedback

The best answer is (a). The reasoning follows.

① $\boxed{?}$ $\gamma = \rho g$? ✓

② $\boxed{?}$ $\rho = p/RT$ ✓ ✓ ✓

2 Eqs
2 Unks ∴ Cracked

$p_{abs} = 0.6\ \text{bar} + 1.0\ \text{bar}$

③ $$\rho = \frac{1.6\text{E}5\ \text{Pa}}{} \left| \frac{\text{kg}\cdot\text{K}}{297\ \text{J}} \right| \frac{}{263.15\ \text{K}} \left| \frac{\text{N}}{\text{Pa}\cdot\text{m}^2} \right| \frac{\text{J}}{\text{N}\cdot\text{m}}$$

$T_{abs} = 273 + (-10)$

$$= 2.047\ \text{kg/m}^3$$

④ $$\therefore\ \gamma = \frac{2.047\ \text{kg}}{\text{m}^3} \left| \frac{9.81\ \text{m}}{\text{s}^2} \right| \frac{\text{N}\cdot\text{s}^2}{\text{kg}\cdot\text{m}}$$

$$= 20.08\ \text{N/m}^3$$

The steps are:

1. Apply the definition of specific weight
2. Apply the IGL
3. Calculate density
4. Calculate specific weight

Problem 2.28

From memory, give the density of water at room conditions.

a. ______________ kg/L
b. ______________ g/L
c. ______________ g/mL
d. ______________ kg/(1000 L)
e. ______________ kg/m^3
f. ______________ $slug/ft^3$
g. ______________ lbm/ft^3
h. ______________ lbm/(US gallon)
i. ______________ lbm/(US quart)

Feedback

Feedback. It is useful to know typical density values of liquid water. These values can be rounded. For example, it is good enough to remember that the density of water is about 8 lbm/gallon.

Density of liquid water is $\rho =$

a. 1.0 kg/L
b. 1000 g/L
c. 1.0 g/mL = 1.0 g/cm^3
d. 1000 kg/(1000 L)
e. 1000 kg/m^3
f. 1.94 $slug/ft^3$
g. 62.4 lbm/ft^3
h. $\approx$ 8 lbm/(US gallon)
i. $\approx$ 2 lbm/(US quart)

Problem 2.29

From memory, give the specific weight of water at room conditions.

a. ________ N/m^3
b. ________ N/L
c. ________ kN/m^3
d. ________ lbf/ft^3
e. ________ lbf/(US gallon)
f. ________ lbf/(US quart)

Feedback

Feedback. It is useful to know typical values of γ for water. Some tips:

1. $\gamma = \rho g$. Thus, $(1.0\,\mathrm{kg/L})(9.81\,\mathrm{m/s^2}) \approx 9.8\,\mathrm{N/L}$
2. Since a mass of 8.0 lbm on earth will have a weight of 8.0 lbf, $\rho \approx 8\,\mathrm{lbm/(US\ gallon)}$ and $\gamma \approx 8\,\mathrm{lbf/(US\ gallon)}$
3. Values can be rounded. For example, it is good enough to remember that $\gamma \approx 8$ lbf/gallon

Specific weight of liquid water is $\gamma =$

a. 9810 N/m^3
b. 9.81 N/L
c. 9.81 kN/m^3
d. 62.4 lbf/ft^3
e. $\approx$ 8 lbf/(US gallon)
f. $\approx$ 2 lbf/(US quart)

Problem 2.30

Which statement is correct?

a. SG (fresh water) > SG (sea water)
b. SG (concrete) > SG (aluminum) > SG(salt water)
c. SG (steel) > SG (aluminum) > SG (concrete) > SG (salt water) > SG (fresh water) > SG (oil)
d. SG (steel) > SG (concrete) > SG (aluminum)
e. SG (oil) > SG (fresh water)

Feedback

Claim: The best choice is (c)

Reasoning: Typical values of specific gravity are:

Material	SG
steel	7.8
aluminum	2.6
concrete	2.3
sea water	1.03
fresh water	1.0
oil	0.8

Problem 2.31

Consider the following statements

I. The reference temperature for SG is $4\,°\mathrm{C}$.
II. Two liquids that are miscible will not mix.
III. A block with $SG > 1$ can float on a liquid.
IV. $\rho_{\mathrm{oil}} = SG_{\mathrm{oil}}(62.4\,\mathrm{lbm/ft^3})$.
V. $\gamma_{\mathrm{H2O}} = \gamma_{\mathrm{oil}}/SG_{\mathrm{oil}}$.

Which of the statements are true? (a) I, IV, and V (b) All, but II (c) All (d) I, IV (e) I, II, and IV

Feedback

Claim: The best choice is (b)

Reasoning: analyze each statement

I. True: this is the reference temperature.
II. False: two liquids which will not mix are *immiscible*
III. True: If $SG_{\mathrm{block}} < SG_{\mathrm{liquid}}$, a block will float
IV. True: the equation is correct; the value of ρ_{H2O} is correct
V. True: the equation is correct

2.32: PROBLEM DEFINITION

Situation:

If a liquid has a specific gravity of 1.7,

a) What is the density in slugs per cubic feet?

b) What is the specific weight in pounds force per cubic feet?

SOLUTION

$$\begin{aligned} SG &= 1.7 \\ SG &= \frac{\rho_l}{\rho_{water,4C}} \end{aligned}$$

a)

$$\begin{aligned} \rho_l &= 1.7\left(1.94\frac{\text{slug}}{\text{ft}^3}\right) \\ \rho_l &= \boxed{3.3\,\frac{\text{slug}}{\text{ft}^3}} \end{aligned}$$

b)

$$\begin{aligned} 32.17\,\text{lbm} &= 1\,\text{slug} \\ & \text{Therefore} \end{aligned}$$

$$\gamma = \frac{\rho}{g} = \left(\frac{3.3\,\text{slug}}{\text{ft}^3}\right)\left(\frac{32.17\,\text{lbm}}{1\,\text{slug}}\right) = \boxed{106\,\frac{\text{lbf}}{\text{ft}^3}}$$

2.33: PROBLEM DEFINITION

Situation:
If you have a bulk modulus of elasticity that is a very large number, then a small change in pressure would cause
a. a very large change in volume
b. a very small change in volume

SOLUTION

Examination of Eq. 2.4 in §2.3 EFM12e shows that the answer is b.

2.34: PROBLEM DEFINITION

Situation:
Dimensions of the bulk modulus of elasticity are
a. the same as the dimensions of pressure/density
b. the same as the dimensions of pressure/volume
c. the same as the dimensions of pressure

SOLUTION

Examination of Eq. 2.4 in §2.3 EFM12e shows that the answer is c. The volume units in the denominator cancel, and the remaining units are pressure.

2.35: PROBLEM DEFINITION

Situation:

Bulk modulus of elasticity of ethyl alcohol and water.
$E_{ethyl} = 1.06 \times 10^9$ Pa.
$E_{water} = 2.15 \times 10^9$ Pa.

Find:

Which substance is easier to compress?
a. ethyl alcohol
b. water

PLAN

Use bulk modulus of elasticity equation.

SOLUTION

The bulk modulus of elasticity is given by:

$$E = -\Delta p \frac{\forall}{\Delta \forall} = \frac{\Delta p}{d\rho/\rho}$$

This means that bulk modulus of elasticity is inversely related to change in density, and to the negative change in volume.
Therefore, the liquid with the smaller bulk modulus is easier to compress.

$\boxed{\text{Correct answer is a. Ethyl alcohol is easier to compress because it has the smaller bulk modulus of e}}$
bulk modulus of elasticity is inversely related to change in density.

Problem 2.36

A liquid is compressed. The change in pressure is 1000 psi. The change in density is 0.02%.

What is the bulk modulus in psi?
(a) 2E6 (b) 5E6 (c) 5E5 (d) 5E4 (e) 2E6

Feedback

Claim: The best choice is (b)

Reasoning:

$\boxed{?}$

$$E_v = \frac{\Delta p}{\Delta \rho / \rho \; ?}$$

$\boxed{?}$

$$\Delta \rho / \rho = \frac{\cancel{\rho_2} - \rho_1}{\rho_1} = 0.02\,\%$$

$(0.02\%)\,\rho_1$

2 Eq
2 Uk $(\frac{\Delta\rho}{\rho}, E_v)$
∴ cracked

① ≡ State 1 (Not compressed)
② ≡ State 2 (compressed)

$$\therefore \quad E_v = \frac{1000\text{ psi}}{(0.02\,E{-}2)} = 5E6\text{ psi}$$

The steps are:
1. Apply the definition of bulk modulus
2. Apply the definition of percent change

Problem 2.37

Start with the premise $E_v = -V\frac{\partial p}{\partial V}$ and prove that $E_v = \rho\frac{\partial p}{\partial \rho}$. (Def: A *premise* is a statement that you believe is true.)

Feedback

My proof is:

① $E_v = -\forall \dfrac{\partial p}{\partial \forall}$

Blue pencil for density so it does not get confused with pressure

② $E_v = -\forall \dfrac{\partial p}{\partial \rho}\dfrac{d\rho}{d\forall}$

③ $\rho = m/\forall$

$\dfrac{d}{dx}(1/x) = -\dfrac{1}{x^2}$: calculus fact

④ $\dfrac{d\rho}{d\forall} = \dfrac{d}{d\forall}\left(\dfrac{m}{\forall}\right) = m\dfrac{d}{d\forall}(1/\forall) = \dfrac{-m}{\forall^2}$

⑤ $\therefore E_v = (-\forall)\left(\dfrac{\partial p}{\partial \rho}\right)\left(\dfrac{-m}{\forall^2}\right) = +\overset{\rho}{\cancel{\dfrac{m}{\forall}}}\dfrac{\partial p}{\partial \rho} = \rho\dfrac{\partial p}{\partial \rho}$

Q.E.D.

The steps are:

1. Start with a true statement
2. Apply the chain rule from calculus
3. Apply the definition of density
4. Take the derivative of density w.r.t. volume
5. Combine Eqs. (2) and (4)

Problem 2.38

(T/F) Air is compressible and sea water is incompressible.

Feedback

Claim: The best choice is F

Reasoning: All materials, including seawater, are compressible.

Problem 2.39

(T/F) If $E_v \downarrow$, then compressibility$\uparrow$.

Feedback

Claim: The best choice is T

Reasoning: If you examine the data for various fluids this trend is evident. For example, compare air to water; $E_v \downarrow$ and compressibility$\uparrow$.

2.40: PROBLEM DEFINITION

Situation:

Pressure is applied to a mass of water.
$\forall = 4300\,\mathrm{cm}^3$, $p = 4 \times 10^6\,\mathrm{N/\,m}^2$.

Find:

Volume after pressure applied (cm^3).

Properties:

From Table A.5 (EFM12e), $E = 2.2 \times 10^9$ Pa

PLAN

1. Use modulus of elasticity equation to calculate volume change resulting from pressure change.
2. Calculate final volume based on original volume and volume change.

SOLUTION

1. Elasticity equation

$$\begin{aligned} E &= -\Delta p \frac{\forall}{\Delta \forall} \\ \Delta \forall &= -\frac{\Delta p}{E} \forall \\ &= -\left[\frac{(4 \times 10^6)\ \mathrm{Pa}}{(2.2 \times 10^9)\ \mathrm{Pa}}\right] 4300\,\mathrm{cm}^3 \\ &= -7.82\,\mathrm{cm}^3 \end{aligned}$$

2. Final volume

$$\begin{aligned} \forall_{final} &= \forall + \Delta \forall \\ &= (4300 - 7.82)\ \mathrm{cm}^3 \end{aligned}$$

$$\boxed{\forall_{final} = 4290\,\mathrm{cm}^3}$$

2.41: PROBLEM DEFINITION

Situation:
Shear stress has dimensions of
a. force/area
b. dimensionless

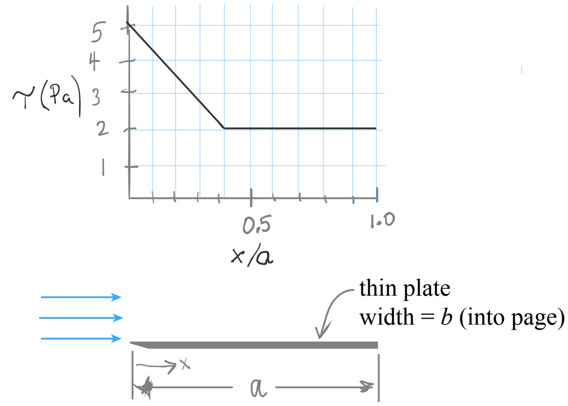
SOLUTION

The answer is (a). See Eq. 2.9 in EFM12e, and discussion.

Problem 2.42

Water is flowing over a thin plate. The length of the plate is $a = 70\,\text{cm}$. The width of the plate is $b = 20\,\text{cm}$. The plot shows the shear stress acting on the top of the plate.

In units of newtons, what is the shear force acting on the top of the plate? (a) 2.0 (b) 0.2 (c) 1.6 (d) 0.8 (e) 0.4



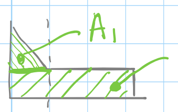
Feedback

Claim: The best choice is (d)

Reasoning:

① $F_s = \int_A \tau\, dA = b \int_{x=0}^{a} \tau(x)\, dx$ — dA = bdx ; ✓ ?

$\underbrace{\int_{x=0}^{a} \tau(x)\, dx}_{\text{Area under curve}}$

② Area = 

$A_1 = \left(\tfrac{1}{2}\right)(0.4\,a)(5-2)\ \text{Pa}$ — a = (0.7 m)

$= 0.42\ \text{Pa}\cdot\text{m}$

$A_2 = (a)(2\,\text{Pa}) = 1.4\ \text{Pa}\cdot\text{m}$

$\therefore$ AREA $= 1.82\ \text{Pa}\cdot\text{m}$

③ $\therefore F_s = (b)(\text{Area}) = (0.2\,\text{m})(1.82\,\text{Pa}\cdot\text{m}) = 0.364\ \text{N}$

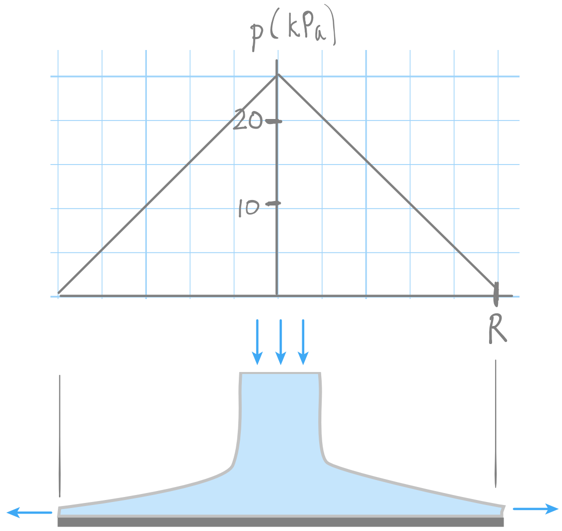
The steps are:

1. Apply the general equation for shear force
2. Evaluate the integral as the area under the curve
3. Do the calcs

Problem 2.43

A round jet of water hits a metal plate creating the pressure distribution that is shown. The radius is $R = 40\,\mathrm{mm}$

In SI units, what is the pressure force on the plate? (a) 40 (b) 80 (c) 5 (d) 10 (e) 20

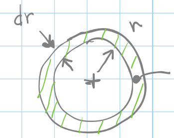


Feedback

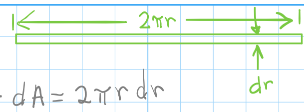
Claim: The best answer is (a)

Reasoning:

① $F_p = \int_A p\,dA$



$dA = 2\pi r\,dr$



$\overset{?}{F_p} = \int_0^R \overset{?}{p(r)}\, 2\pi r\, dr$

② $\boxed{?}$ $p(r) = \overset{25\text{ kPa}}{p_{max}}\,(1 - r/R)$

2 Eqs
2 Uks
∴ cracked

③ $\therefore\; F_p = p_{max}\, 2\pi \int_0^R \left(r - r^2/R\right) dr$

$= 2\pi p_{max}\left(\frac{r^2}{2} - \frac{r^3}{3R}\right)\Big|_0^R = \approx \underbrace{\left(\frac{R^2}{2} - \frac{R^2}{3}\right)}_{R^2/6}$

$= \frac{\pi p_{max} R^2}{3}$

④ $\therefore\; F_p = (\pi/3)(25\text{ kPa})(40E\text{-}3^2\ \text{m}^2)$

$= 0.0419$ kN

The steps are:

1. Apply the general equation for the pressure force; note the use of polar coordinates
2. Apply the slope-intercept formula (straight line) to write an equation for $p(r)$
3. Solve for the goal (algebraic equation)
4. Do the calcs

Problem 2.44

A liquid is flowing in a round pipe. The liquid exerts a constant shear stress of $\tau = 30\,\text{Pa}$ on the inside wall of the pipe. The pipe cross section area is $700\,\text{cm}^2$. The pipe length is $20\,\text{m}$.

In SI units, what is the shear force on the pipe? (a) 490 (b) 330 (c) 210 (d) 560 (e) 120

Feedback

Claim: The best answer is (d)

Reasoning:

(1) $\boxed{?}$ $F_s = \tau_0 A$, $\quad A \to \pi \overset{?}{D} L$

(2) $A = \pi \boxed{?} D^2/4$

2 Eqs, 2 Uks ∴ cracked

(3) $D = \sqrt{4A/\pi}$ ∴ $F_s = \tau_0 \pi \sqrt{\frac{4A}{\pi}}\, L = 2\tau_0 L \sqrt{\pi A}$

(4) $F_s = 2 \left| \frac{30\,\text{N}}{\text{m}^2} \right| 20\,\text{m} \left| \left[\pi \left| \frac{700\,\text{cm}^2}{100^2} \right| \frac{\text{m}^2}{\text{cm}^2} \right]^{1/2} \right.$

$= 562.7\,\text{N}$

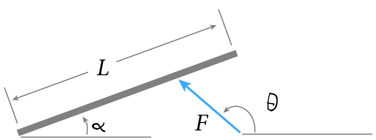
The steps are:

1. Apply the equation for shear force
2. Apply the formula for the area of a circle
3. Solve for the goal (algebraic equation)
4. Do the calcs

Problem 2.45

A flowing fluid creates a pressure and a shear stress distribution on a square plate. The resultant force is $F = 170\,\mathrm{N}$. The length of one side of the plate is $L = 70\,\mathrm{cm}$. The angles are $\alpha = 20°$ and $\theta = 140°$.

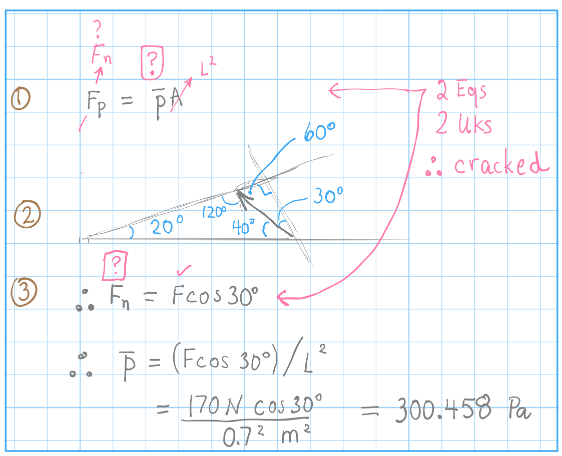
What is the average pressure in Pa gage? (a) 170 (b) 340 (c) 420 (d) 520 (e) 300



Feedback

Claim: The best choice is (e)

Reasoning:



The steps are:

1. Apply the pressure force formula
2. Sketch triangles and then solve these triangles
3. Solve for the goal

Problem 2.46

(T/F) In general, pressure p is given by F_n/A, where F_n is a normal force that acts on an area A.

Feedback

Claim: The best choice is F.

Reasoning. While $p = F_n/A$ is sometimes true, there are many situations in which this formula gives average pressure instead of pressure at a point. Pressure is best defined as a derivative like this: $p = \lim_{\Delta A \to 0} \frac{\Delta F_n}{\Delta A}$.

Problem 2.47

(T/F) In general, the force due to pressure F_p is given by $F_p = pA$, where p is pressure and A is area.

Feedback

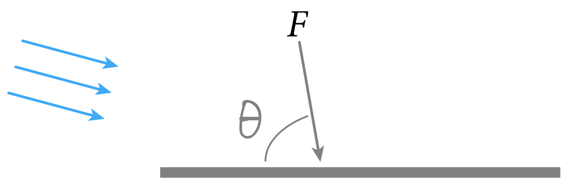
Claim. The best choice is F.

Reasoning. The general formula for the pressure force is $F_p = \int_A p dA$. The formula $F_p = pA$ is only true when average pressure is used or when pressure is uniform.

Problem 2.48

A flowing fluid creates a pressure and a shear stress distribution on the top of a square plate. The resultant force is $F = 220\,\text{N}$. The length of one side of the plate is $L = 120\,\text{cm}$. The angle is $\theta = 80°$.

In pascals, what is the average shear stress acting on the top of the plate? (a) 77 (b) 17 (c) 67 (d) 47 (e) 27



Feedback

Claim: The best choice is (e)

Reasoning:

① $F_s = \bar{\tau} A$ — F_s: $F\cos\theta$; $\bar{\tau}$: ?; A: L^2 — 1 EQ, 1 uk ⇒ ∴ cracked

② $$\bar{\tau} = \frac{(F\cos\theta)}{L^2} = \frac{220\ \text{N}}{1.2^2\ \text{m}^2}\cos 80°$$

$$= 26.530\ \text{Pa}$$

The steps are:

1. Apply the shear force equation
2. Do the calcs

Problem 2.49

The dimensions of viscosity are:
(a) F/LT (b) FT^2/L (c) FL/T (d) FT/L^2 (e) F/L^2

Feedback

Claim: The best choice is (d)

Reasoning:

1 $[\mu] = \dfrac{M}{LT}$

2 $F = ML/T^2$

$\therefore M = FT^2/L$

3 $\therefore [\mu] = \dfrac{FT^{\cancel{2}}}{L} \Big| \dfrac{1}{L\cancel{T}} = \dfrac{FT}{L^2}$

The steps are:

1. List the primary dimensions of viscosity
2. Find the dimensions of mass from $\Sigma F = ma$
3. Combine the results of steps 1 and 2

Problem 2.50

Consider the following statements:

I. $[\tau] = F/L^2$
II. $[\tau] = M/L \cdot T$
III. $[\mu] = F \cdot T/L^2$
IV. $[\mu] = M/L \cdot T$
V. $[dV/dy] = L/T$

Which statements are true? (a) All (b) All except V (c) I, III (d) I, III, and IV (e) I, II, and III

Feedback

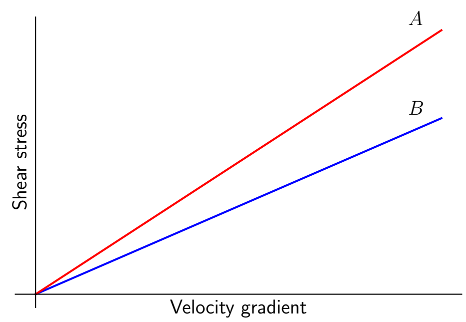
Claim: The best choice is (d)

Consider the following statements:

I. True: the dimensions of τ are force/area
II. False: force/area has dimensions of $M/L \cdot T^2$
III. True: the dimensions of μ are (force/area) x (time)
IV. True: the dimensions of μ are (mass) / (length $\cdot$ time)
V. False: the dimensions of velocity gradient are T^{-1}

Problem 2.51

(T/F) If line A is for water at temperature T_A and line B is for water at T_B, then $T_A < T_B$



Feedback

Claim: The best choice is true.

True. The reasoning is:

1. Since $\tau = \mu dV/dy$, the slope of each line in the given plot is μ.
2. Thus, $\mu_A > \mu_B$
3. For a liquid: If $T \uparrow$, then $\mu \downarrow$
4. Thus, $T_B > T_A$

2.52: PROBLEM DEFINITION

Situation:
For the velocity gradient dV/dy
a. The coordinate axis for dy is parallel to the velocity vector
b. The coordinate axis for dy is perpendicular to the velocity vector

SOLUTION

The answer is (b). See definition of Velocity Gradient in the text.

2.53: PROBLEM DEFINITION

Situation:

The no-slip condition

a. only applies to ideal flow

b. only applies to rough surfaces

c. means velocity, V, is zero at the wall

d. means velocity, V, is the velocity of the wall

SOLUTION

The answer is (d); velocity, V, is the velocity of the wall.

2.54: PROBLEM DEFINITION

Situation:
Which of these materials will flow (deform) with even a small shear stress applied?

a. a Bingham plastic
b. a Newtonian fluid

SOLUTION

The answer is (b); see Fig. 2.14 in EFM12e.

2.55: PROBLEM DEFINITION

Situation:
At a point in a flowing fluid, the shear stress, τ, is 3×10^{-4} psi, and the velocity gradient is 1 s^{-1}.

Find:
a. What is the viscosity in traditional units (in lbf, in^2, and s)?
b. Convert this viscosity to standard SI units.
c. Is this fluid more, or less, viscous than water?

SOLUTION

a.

$$\begin{aligned}\tau &= \mu \frac{dV}{dy} \\ \mu &= \frac{\tau}{dV/dy} = \left(\frac{3 \times 10^{-4}\,\text{lbf}}{\text{in}^2}\right)\left(\frac{\text{s}}{1}\right) \\ \mu &= \boxed{3 \times 10^{-4}\,\frac{\text{lbf} \cdot \text{s}}{\text{in}^2}} \text{ or } \mu = \boxed{4.32 \times 10^{-2}\,\frac{\text{lbf} \cdot \text{s}}{\text{ft}^2}}\end{aligned}$$

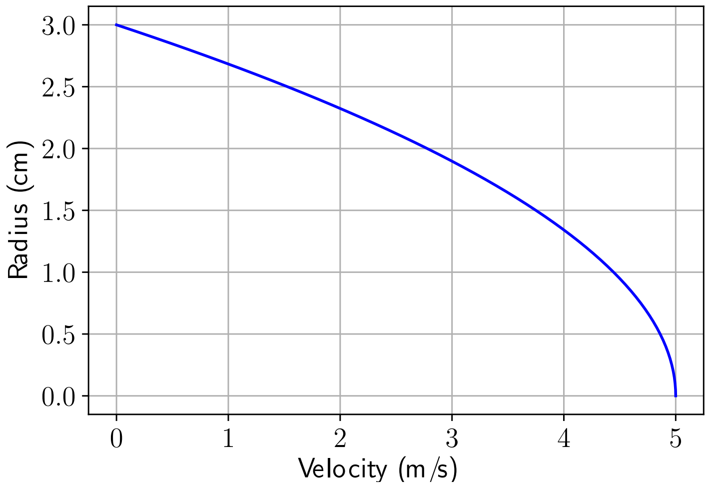
b. Convert to SI units, using grid method

$$\begin{aligned}\mu &= \left(\frac{3 \times 10^{-4}\,\text{lbf} \cdot \text{s}}{\text{in}^2}\right)\left(\frac{144\,\text{in}^2}{1\,\text{ft}^2}\right)\left(\frac{(3.281)^2\,\text{ft}^2}{1\,\text{m}^2}\right)\left(\frac{4.448\,\text{N}}{1\,\text{lbf}}\right) \\ \mu &= \boxed{2.069\,\frac{\text{N} \cdot \text{s}}{\text{m}^2}}\end{aligned}$$

c. The fluid is more viscous than water, based upon a comparison to tabulated values for water. The viscosity of water ranges from 2.8×10^{-4} to 1.8×10^{-3} $\frac{\text{N} \cdot \text{s}}{\text{m}^2}$ depending upon temperature (Table A.5, EFM12e).

Problem 2.56

The following figure shows a velocity profile in a round pipe for a fluid with a kinematic viscosity of $1 \times 10^{-6}\,\mathrm{m^2/s}$ and a density of $1000\,\mathrm{kg/m^3}$.



The magnitude of the shear stress at the wall in SI units is:
(a) 0.062 (b) 0.0015 (c) 0.33 (d) 3.00 (e) 6.20

Feedback

Claim: The best choice is (c)

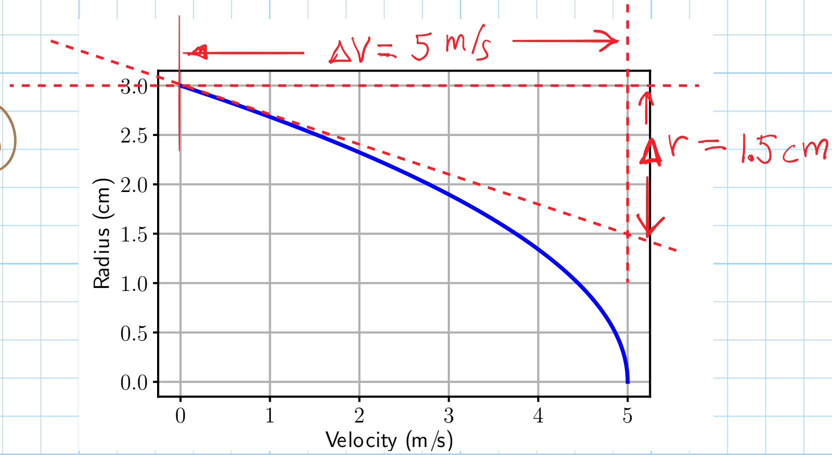
Reasoning:

1. $\boxed{?}\ \tau = \overset{?}{\mu} \left.\frac{\overset{?}{dV}}{dr}\right|_{r=0}$

2. $\nu = \frac{\boxed{?}\,\mu}{\rho}$

3 eqs
3 uks
∴ cracked

3.



4. ∴ $\tau = \rho\nu \frac{\Delta V}{\Delta r}$

5. $= \frac{1000\,\cancel{kg}}{\cancel{m^3}} \left| \frac{10^{-6}\,\cancel{m^2}}{\cancel{s}} \right| \frac{5\,\cancel{m}}{\cancel{s}} \left| \frac{1}{1.5E{-2}\,\cancel{m}} \right| \frac{Pa \cdot \cancel{m} \cdot \cancel{s^2}}{\cancel{kg}}$

$= \frac{5E{-3}}{1.5E{-2}} = 3.33E{-1}\ Pa$

The steps are

1. Apply the viscosity equation
2. Apply the definition of kinematic viscosity
3. Calculate $\frac{dV}{dr}$ using the rise/run of the tangent line
4. Build an equation for the goal
5. Do the calcs

2.57: PROBLEM DEFINITION

Situation:
Water flows near a wall. The velocity distribution is

$$u(y) = a\left(\frac{y}{b}\right)^{1/6}$$

$a = 10\,\mathrm{m/s}$, $b = 2\,\mathrm{mm}$ and y is the distance (mm) from the wall.

Find:
Shear stress in the water at $y = 1$ mm.

Properties:
Table A.5 (EFM12e); water at 20 °C: $\mu = 1.00 \times 10^{-3}\,\mathrm{N\cdot s/m^2}$.

SOLUTION

Take the derivative of the velocity equation to get $\frac{du}{dy}$

$$\begin{aligned}
\frac{du}{dy} &= \frac{d}{dy}\left[a\left(\frac{y}{b}\right)^{1/6}\right] \\
&= \frac{a}{b^{1/6}}\frac{1}{6y^{5/6}} \\
&= \frac{a}{6b}\left(\frac{b}{y}\right)^{5/6}
\end{aligned}$$

du/dy (at $y = 1\,\mathrm{mm}$)

$$\begin{aligned}
\frac{du}{dy} &= \frac{a}{6b}\left(\frac{b}{y}\right)^{5/6} \\
&= \frac{10\,\mathrm{m/s}}{6 \times 0.002\,\mathrm{m}}\left(\frac{2\,\mathrm{mm}}{1\,\mathrm{mm}}\right)^{5/6} \\
&= 1485\,\mathrm{s^{-1}}
\end{aligned}$$

Shear Stress

$$\begin{aligned}
\tau_{y=1\,\mathrm{mm}} &= \mu\frac{du}{dy} \\
&= \left(1.00 \times 10^{-3}\frac{\mathrm{N\cdot s}}{\mathrm{m^2}}\right)\left(1485\,\mathrm{s^{-1}}\right) \\
&= 1.485\,\mathrm{Pa}
\end{aligned}$$

$$\boxed{\tau\,(y = 1\,\mathrm{mm}) = 1.49\,\mathrm{Pa}}$$

2.58: PROBLEM DEFINITION

Situation:

A liquid flows between parallel boundaries.
$y_0 = 0.0\,\text{mm}$, $V_0 = 0.0\,\text{m/s}$.
$y_1 = 1.0\,\text{mm}$, $V_1 = 1.0\,\text{m/s}$.
$y_2 = 2.0\,\text{mm}$, $V_2 = 1.99\,\text{m/s}$.
$y_3 = 3.0\,\text{mm}$, $V_3 = 2.98\,\text{m/s}$.

Find:

(a) Maximum shear stress.
(b) Location where minimum shear stress occurs.

SOLUTION

(a) Maximum shear stress

$$
\begin{aligned}
\tau &= \mu dV/dy \\
\tau_{\max} &\approx \mu(\Delta V/\Delta y) \text{ next to wall} \\
\tau_{\max} &= (10^{-3}\text{N}\cdot\text{s/m}^2)((1\text{ m/s})/0.001\text{ m}) \\
& \boxed{\tau_{\max} = 1.0\text{ N/m}^2}
\end{aligned}
$$

(b)The $\boxed{\text{minimum shear stress will occur midway between the two walls}}$. Its magnitude will be zero because the velocity gradient is zero at the midpoint.

2.59: PROBLEM DEFINITION

Situation:

Glycerin is flowing in between two stationary plates. The velocity distribution is

$$u = -\frac{1}{2\mu}\frac{dp}{dx}\left(By - y^2\right)$$

$dp/dx = -1.2\,\mathrm{kPa/\,m}$, $B = 5\,\mathrm{cm}$.

Find:

Velocity and shear stress at a distance of 11 mm from wall (i.e. at $y = 11\,\mathrm{mm}$).

Velocity and shear stress at the wall (i.e. at $y = 0\,\mathrm{mm}$).

Properties:

Glycerin ($20\,^\circ\mathrm{C}$), Table A.4 (EFM12e): $\mu = 1.41\,\mathrm{N\cdot s/\,m^2}$.

PLAN

Find velocity by direct substitution into the specified velocity distribution.

Find shear stress using the definition of viscosity: $\tau = \mu\,(du/dy)$, where the rate-of-strain (i.e. the derivative du/dy) is found by differentiating the velocity distribution.

SOLUTION

a.) Velocity (at $y = 11\,\mathrm{mm}$)

$$\begin{aligned}
u &= -\frac{1}{2\mu}\frac{dp}{dx}\left(By - y^2\right) \\
&= -\frac{1}{2\,(1.41\,\mathrm{N\cdot s/\,m^2})}\left(-1200\,\mathrm{N/\,m^3}\right)\left((0.05\,\mathrm{m})\,(0.011\,\mathrm{m}) - (0.011\,\mathrm{m})^2\right) \\
&= 0.1826\frac{\mathrm{m}}{\mathrm{s}}
\end{aligned}$$

$$\boxed{u\,(y = 11\,\mathrm{mm}) = 0.183\,\mathrm{m/\,s}}$$

dV/dy (general expression)

$$\begin{aligned}
\frac{du}{dy} &= \frac{d}{dy}\left(-\frac{1}{2\mu}\frac{dp}{dx}\left(By - y^2\right)\right) \\
&= \left(-\frac{1}{2\mu}\right)\left(\frac{dp}{dx}\right)\frac{d}{dy}\left(By - y^2\right) \\
&= \left(-\frac{1}{2\mu}\right)\left(\frac{dp}{dx}\right)(B - 2y)
\end{aligned}$$

dV/dy (at $y = 11\,\text{mm}$)

$$\begin{aligned}
\frac{du}{dy} &= \left(-\frac{1}{2\mu}\right)\left(\frac{dp}{dx}\right)(B-2y) \\
&= \left(-\frac{1}{2\,(1.41\,\text{N}\cdot\text{s}/\,\text{m}^2)}\right)\left(-1200\frac{\text{N}}{\text{m}^3}\right)(0.05\,\text{m} - 2\times 0.011\,\text{m}) \\
&= 11.91\,\text{s}^{-1}
\end{aligned}$$

Use definition of viscosity to get shear stress

$$\begin{aligned}
\tau &= \mu\frac{du}{dy} \\
&= \left(1.41\frac{\text{N}\cdot\text{s}}{\text{m}^2}\right)\left(11.91\,\text{s}^{-1}\right) \\
&= 16.80\,\text{Pa}
\end{aligned}$$

$$\boxed{\tau\,(y = 11\,\text{mm}) = 16.8\,\text{Pa}}$$

b.) Velocity (at $y = 0\,\text{mm}$)

$$\begin{aligned}
u &= -\frac{1}{2\mu}\frac{dp}{dx}\left(By - y^2\right) \\
&= -\frac{1}{2\,(1.41\,\text{N}\cdot\text{s}/\,\text{m}^2)}\left(-1600\,\text{N}/\,\text{m}^3\right)\left((0.05\,\text{m})\,(0\,\text{m}) - (0\,\text{m})^2\right) \\
&= 0.00\frac{\text{m}}{\text{s}}
\end{aligned}$$

$$\boxed{u\,(y = 0\,\text{mm}) = 0\,\text{m}/\,\text{s}}$$

dV/dy (at $y = 0\,\text{mm}$)

$$\begin{aligned}
\frac{du}{dy} &= \left(-\frac{1}{2\mu}\right)\left(\frac{dp}{dx}\right)(B-2y) \\
&= \left(-\frac{1}{2\,(1.41\,\text{N}\cdot\text{s}/\,\text{m}^2)}\right)\left(-1200\frac{\text{N}}{\text{m}^3}\right)(0.05\,\text{m} - 2\times 0\,\text{m}) \\
&= 21.28\,\text{s}^{-1}
\end{aligned}$$

Shear stress (at $y = 0\,\text{mm}$)

$$\begin{aligned}
\tau &= \mu\frac{du}{dy} \\
&= \left(1.41\frac{\text{N}\cdot\text{s}}{\text{m}^2}\right)\left(21.28\,\text{s}^{-1}\right) \\
&= 30.00\,\text{Pa}
\end{aligned}$$

$$\boxed{\tau\,(y = 0\,\text{mm}) = 30.0\,\text{Pa}}$$

REVIEW

1. As expected, the velocity at the wall (i.e. at $y = 0$) is zero due to the no slip condition.

2. As expected, the shear stress at the wall is larger than the shear stress away from the wall. This is because shear stress is maximum at the wall and zero along the centerline (i.e. at $y = B/2$).

2.60: PROBLEM DEFINITION

Situation:

Oil (SAE 10W30) fills the space between two plates.
$\Delta y = 1/4 = 0.25\,\text{in}$, $u = 12\,\text{ft/s}$.

Lower plate is at rest.

Find:

Shear stress in oil.

Properties:

Oil (SAE 10W30 @ 150 °F) from Figure A.2 (EFM12e): $\mu = 5.2 \times 10^{-4}$ lbf·s/ft^2.

Assumptions:

1.) Assume oil is a Newtonian fluid.
2.) Assume Couette flow (linear velocity profile).

SOLUTION

dV/dy - linear velocity profile

$$\begin{aligned} \frac{du}{dy} &= \frac{\Delta u}{\Delta y} \\ &= \frac{12\,\text{ft/s}}{(0.25/12)\ \text{ft}} \\ \frac{du}{dy} &= 576\,\text{s}^{-1} \end{aligned}$$

Newton's law of viscosity - Newtonian fluid

$$\begin{aligned} \tau &= \mu\left(\frac{du}{dy}\right) \\ &= \left(5.2 \times 10^{-4}\frac{\text{lbf}\cdot\text{s}}{\text{ft}^2}\right) \times \left(576\frac{1}{\text{s}}\right) \\ &= 0.300\frac{\text{lbf}}{\text{ft}^2} \end{aligned}$$

$$\boxed{\tau = 0.300\ \frac{\text{lbf}}{\text{ft}^2}}$$

2.61: PROBLEM DEFINITION

Situation:

A sliding plate viscometer is used to measure fluid viscosity.
$A = 50 \times 100\,\text{mm}$, $\Delta y = 1\,\text{mm}$.
$V = 10\,\text{m/s}$, $F = 3\,\text{N}$.

Find:

Viscosity of the fluid.

Assumptions:

Linear velocity distribution.

PLAN

1. The shear force τ is a force/area.
2. Use equation for viscosity to relate shear force to the velocity distribution.

SOLUTION

1. Calculate shear force

$$\begin{aligned}\tau &= \frac{\text{Force}}{\text{Area}} \\ \tau &= \frac{3\,\text{N}}{50\,\text{mm} \times 100\,\text{mm}} \\ \tau &= 600\,\text{N/m}^2\end{aligned}$$

2. Find viscosity

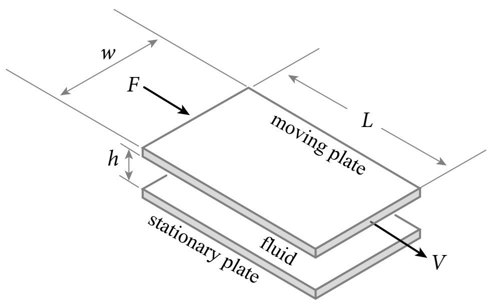
$$\begin{aligned}\mu &= \frac{\tau}{\left(\frac{dV}{dy}\right)} \\ \mu &= \frac{600\,\text{N/m}^2}{[10\,\text{m/s}]/[1\,\text{mm}]} \times \frac{1\,\text{m}}{1000\,\text{mm}}\end{aligned}$$

$$\boxed{\mu = 6.0 \times 10^{-2}\,\frac{\text{N}\cdot\text{s}}{\text{m}^2}}$$

Problem 2.62

Viscosity is being measured with the sliding plate viscometer that is shown. The parameters are: $F = 5\,\mathrm{N}$, $h = 0.5\,\mathrm{mm}$, $L = 20\,\mathrm{cm}$, $w = 10\,\mathrm{cm}$, and $V = 7\,\mathrm{m/s}$.

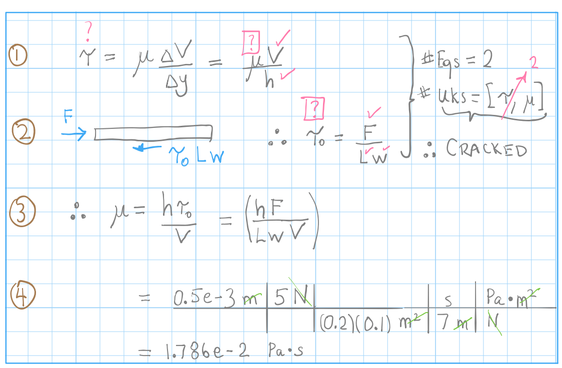
In $\mathrm{mPa \cdot s}$, the viscosity of the fluid is:
(a) 2 (b) 84 (c) 27 (d) 18 (e) 8



Feedback

Claim: The best choice is (d)

Reasoning: The flow in a viscometer is usually modeled as a Couette flow. Thus, the solution can be found like this:



The steps are:

1. Apply the viscosity equation to a Couette flow
2. Draw a FBD. Apply $\Sigma F_x = 0$.
3. Build an equation for the goal
4. Do the calcs

2.63: PROBLEM DEFINITION

Situation:

Laminar flow occurs between two horizontal parallel plates.

$\frac{dp}{ds}$ is constant, and its sign is negative.

The velocity distribution is given by

$$u = -\frac{1}{2\mu}\frac{dp}{ds}\left(Hy - y^2\right) - u_t\frac{y}{H}$$

Pressure p decreases with distance s, and the speed of the upper plate is u_t. Note that u_t has a negative value to represent that the upper plate is moving to the left.

Moving plate: $y = H$.

Stationary plate: $y = 0$.

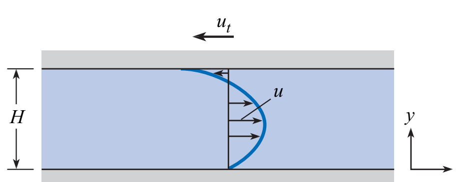
Find:

(a) Whether shear stress is greatest at the moving or stationary plate.

(b) Location of zero shear stress.

(c) Derive an expression for plate speed to make the shear stress zero at $y = 0$.

Sketch:



PLAN

By inspection, the slope of the velocity profile (du/dy) is larger at the moving plate. Thus, we expect shear stress τ to be larger at $y = H$. To check this idea, find shear stress using the definition of viscosity: $\tau = \mu\,(du/dy)$. Evaluate and compare the shear stress at the locations $y = H$ and $y = 0$.

SOLUTION

Part (a)

1. Shear stress, from definition of viscosity

$$\begin{aligned}
\tau &= \mu\frac{du}{dy} \\
&= \mu\frac{d}{dy}\left[-\frac{1}{2\mu}\frac{dp}{ds}\left(Hy-y^2\right)+u_t\frac{y}{H}\right] \\
&= \mu\left[-\frac{H}{2\mu}\frac{dp}{ds}+\frac{y}{\mu}\frac{dp}{ds}+\frac{u_t}{H}\right] \\
\tau(y) &= -\frac{(H-2y)}{2}\frac{dp}{ds}+\frac{\mu u_t}{H}
\end{aligned}$$

Shear stress at $y = H$

$$\begin{aligned}
\tau(y=H) &= -\frac{(H-2H)}{2}\frac{dp}{ds}+\frac{\mu u_t}{H} \\
&= \frac{H}{2}\left(\frac{dp}{ds}\right)+\frac{\mu u_t}{H} \qquad (1)
\end{aligned}$$

2. Shear stress at $y = 0$

$$\begin{aligned}
\tau(y=0) &= -\frac{(H-0)}{2}\frac{dp}{ds}+\frac{\mu u_t}{H} \\
&= -\frac{H}{2}\left(\frac{dp}{ds}\right)+\frac{\mu u_t}{H} \qquad (2)
\end{aligned}$$

Since pressure decreases with distance, the pressure gradient dp/ds is negative. Since the upper wall moves to the left, u_t is negative. Thus, maximum shear stress occurs at $y = H$ because both terms in Eq. (1) have the same sign (they are both negative.) In other words,

$$|\tau(y=H)| > |\tau(y=0)|$$

.

$\boxed{\text{Maximum shear stress occur at } y = H}$.

Part (b)
Use definition of viscosity to find the location (y) of zero shear stress

$$\begin{aligned}
\tau &= \mu\frac{du}{dy} \\
&= -\mu(1/2\mu)\frac{dp}{ds}(H-2y)+\frac{u_t\mu}{H} \\
&= -(1/2)\frac{dp}{ds}(H-2y)+\frac{u_t\mu}{H}
\end{aligned}$$

Set $\tau = 0$ and solve for y

$$
\begin{aligned}
0 &= -(1/2)\frac{dp}{ds}(H-2y)+\frac{u_t\mu}{H} \\
& \boxed{y=\frac{H}{2}-\frac{\mu u_t}{H dp/ds}}
\end{aligned}
$$

Part (c)

$$
\begin{aligned}
\tau &= \mu\frac{du}{dy}=0 \text{ at } y=0 \\
\frac{du}{dy} &= -(1/2\mu)\frac{dp}{ds}(H-2y)+\frac{u_t}{H} \\
\text{Then, at } y &= 0: du/dy=0=-(1/2\mu)\frac{dp}{ds}H+\frac{u_t}{H} \\
\text{Solve for } u_t &: \boxed{u_t=(1/2\mu)\frac{dp}{ds}H^2} \\
\textit{Note} &: \text{ because } \frac{dp}{ds}<0, u_t<0.
\end{aligned}
$$

Problem 2.64

For the given situation, which equation gives the magnitude of the shear stress acting on the wall? (a) $2\mu V_o/R$ (b) $4\mu V_o/R$ (c) $\mu V_o/2R$ (d) $\mu V_o/4R$ (e) $\mu V_o/16R$

Situation

If statements (a) to (c) are true,

a. A Newtonian fluid is flowing in a round pipe
b. The flow is fully developed
c. The flow is laminar

Then, the velocity profile is given by

$$V(r) = V_o(1-(r/R)^2)$$

where

a. $V(r)$ = the fluid velocity at radius r (m/s)
b. V_0 = the fluid velocity at the center of the pipe which is $V(r=0)$ (m/s)
c. R = the radius of the pipe (m)

Feedback

Claim: The best choice is (a)

Reasoning:

1 $$\tau_0 = \mu \frac{dV}{dr}\Big|_{r=R}$$

2 $$= \mu \frac{d}{dr}\left[V_0\left(1-(r/R)^2\right)\right]\Big|_{r=R}$$

3 $$= \mu\left[\frac{dV_0}{dr} - \frac{d}{dr}\left(V_0\left(\frac{r}{R}\right)^2\right)\right]_{r=R}$$

4 $$= \mu\left[0 - V_0\frac{2r}{R^2}\right]_{r=R}$$

5 $$= \left(-\mu V_0 2\frac{R}{R^2}\right) = \frac{-2\mu V_0}{R}$$

The steps are:

1. Apply the viscosity equation
2. Plug in the given velocity profile
3. Apply the sum rule for a derivative
4. Take the derivatives
5. Derive the final result

2.65: PROBLEM DEFINITION

Situation:

A cylinder falls inside a pipe filled with oil.
$d = 100\,\text{mm}$, $D = 100.5\,\text{mm}$.
$\ell = 200\,\text{mm}$, $W = 15\,\text{N}$.

Find:

Speed at which the cylinder slides down the pipe.

Properties:

SAE 20W oil (10°C) from Figure A.2 (EFM12e): $\mu = 0.35$ N·s/m^2.

Assumptions:

Assume that buoyant forces can be neglected.

SOLUTION

$$\begin{aligned}
\tau &= \mu \frac{dV}{dy} \\
\frac{W}{\pi d \ell} &= \frac{\mu V_{\text{fall}}}{(D-d)/2} \\
V_{\text{fall}} &= \frac{W(D-d)}{2\pi d \ell \mu} \\
V_{\text{fall}} &= \frac{15\,\text{N}(0.5 \times 10^{-3}\,\text{m})}{(2\pi \times 0.1\,\text{m} \times 0.2\,\text{m} \times 3.5 \times 10^{-1}\,\text{N}\,\text{s}/\,\text{m}^2)} \\
&\boxed{V_{\text{fall}} = 0.17\text{m/s}}
\end{aligned}$$

2.66: PROBLEM DEFINITION

Situation:

A disk is rotated very close to a solid boundary with oil in between.
$\omega_a = 1\,\mathrm{rad/\,s}$, $r_2 = 2\,\mathrm{cm}$, $r_3 = 3\,\mathrm{cm}$.
$\omega_b = 2\,\mathrm{rad/\,s}$, $r_b = 3\,\mathrm{cm}$.
$H = 2\,\mathrm{mm}$, $\mu_c = 0.01\,\mathrm{N\,s/\,m^2}$.

Find:

(a) Ratio of shear stress at 2 cm to shear stress at 3 cm.
(b) Speed of oil at contact with disk surface.
(c) Shear stress at disk surface.

Assumptions:

Linear velocity distribution: $dV/dy = V/y = \omega r/y$.

SOLUTION

(a) Ratio of shear stresses

$$\begin{aligned} \tau &= \mu\frac{dV}{dy} = \frac{\mu\omega r}{y} \\ \frac{\tau_2}{\tau_3} &= \frac{\mu \times 1 \times 2/y}{\mu \times 1 \times 3/y} \\ & \boxed{\frac{\tau_2}{\tau_3} = \frac{2}{3}} \end{aligned}$$

(b) Speed of oil

$$\begin{aligned} V &= \omega r = 2 \times 0.03 \\ & \boxed{V = 0.06\mathrm{m/s}} \end{aligned}$$

(c) Shear stress at surface

$$\begin{aligned} \tau &= \mu\frac{dV}{dy} = 0.01\,\mathrm{N\,s/\,m^2} \times \frac{0.06\,\mathrm{m/\,s}}{0.002\,\mathrm{m}} \\ & \boxed{\tau = 0.30\ \mathrm{N/m^2}} \end{aligned}$$

2.67: PROBLEM DEFINITION

Situation:

A disk is rotated in a container of oil to damp the motion of an instrument.

Find:

Derive an equation for damping torque as a function of D, S, ω and μ.

PLAN

Apply the Newton's law of viscosity.

SOLUTION

Shear stress

$$\begin{aligned}\tau &= \mu\frac{dV}{dy} \\ &= \frac{\mu r\omega}{s}\end{aligned}$$

Find differential torque—on an elemental strip of area of radius r the differential shear force will be τdA or $\tau(2\pi r dr)$. The differential torque will be the product of the differential shear force and the radius r.

$$\begin{aligned}dT_{\text{one side}} &= r[\tau(2\pi r dr)] \\ &= r\left[\frac{\mu r\omega}{s}(2\pi r dr)\right] \\ &= \frac{2\pi\mu\omega}{s}r^3 dr \\ dT_{\text{both sides}} &= 4\left(\frac{r\pi\mu\omega}{s}\right)r^3 dr\end{aligned}$$

Integrate

$$\begin{aligned}T &= \int_0^{D/2}\frac{4\pi\mu\omega}{s}r^3 dr \\ T &= \frac{1}{16}\frac{\pi\mu\omega D^4}{s}\end{aligned}$$

2.68: PROBLEM DEFINITION

Situation:

One type of viscometer involves the use of a rotating cylinder inside a fixed cylinder.

$T_{\min} = 50\,^\circ\mathrm{F}$, $T_{\max} = 200\,^\circ\mathrm{F}$.

Find:

(a) Design a viscometer that can be used to measure the viscosity of motor oil.

Assumptions:

Motor oil is SAE 10W-30. Data from Fig A-2 (EFM12e): μ will vary from about 2×10^{-4}lbf-s/ft^2 to 8×10^{-3}lbf-s/ft^2.

Assume the only significant shear stress is developed between the rotating cylinder and the fixed cylinder.

Assume we want the maximum rate of rotation (ω) to be 3 rad/s.

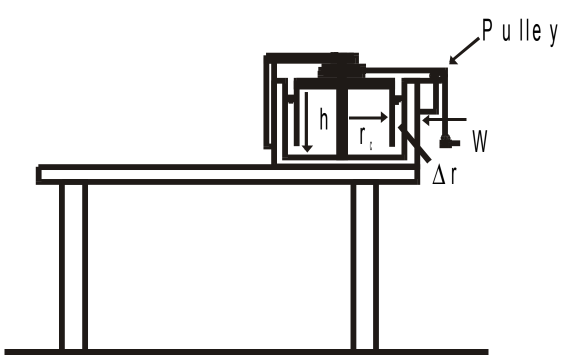
Maximum spacing is 0.05 in.

SOLUTION

One possible design solution is given below.
Design decisions:

1. Let $h = 4.0$ in. $= 0.333$ ft
2. Let I.D. of fixed cylinder $= 9.00$ in. $= 0.7500$ ft.
3. Let O.D. of rotating cylinder $= 8.900$ in. $= 0.7417$ ft.

Let the applied torque, which drives the rotating cylinder, be produced by a force from a thread or small diameter monofilament line acting at a radial distance r_s. Here r_s is the radius of a spool on which the thread of line is wound. The applied force is produced by a weight and pulley system shown in the sketch below.



The relationship between μ, r_s, ω, h, and W is now developed.

$$T = r_c F_s \tag{1}$$

where $T =$ applied torque
$r_c =$ outer radius of rotating cylinder
$F_s =$ shearing force developed at the outer radius of the rotating cylinder but $F_s = \tau A_s$ where $A_s =$ area in shear $= 2\pi r_c h$

$$\tau = \mu dV/dy \approx \mu \Delta V/\Delta r \text{ where } \Delta V = r_c\omega \text{ and } \Delta r = \text{ spacing}$$

Then $T = r_c(\mu\Delta V/\Delta r)(2\pi r_c h)$

$$= r_c\mu(\frac{r_c\omega}{\Delta r})(2\pi r_c h) \tag{2}$$

But the applied torque $T = Wr_s$ so Eq. (2) become

$$Wr_s = r_c^3\mu\omega(2\pi)\frac{h}{\Delta r}$$

Or

$$\mu = \frac{Wr_s\Delta r}{2\pi\omega h r_c^3} \tag{3}$$

The weight W will be arbitrarily chosen (say 2 or 3 oz.) and ω will be determined by measuring the time it takes the weight to travel a given distance. So $r_s\omega = V_{\text{fall}}$ or $\omega = V_{\text{fall}}/r_s$. Equation (3) then becomes

$$\mu = \left(\frac{W}{V_f}\right)\left(\frac{r_s^2}{r_c^3}\right)\left(\frac{\Delta r}{2\pi h}\right)$$

In our design let $r_s = 2$ in. $= 0.1667$ ft. Then

$$\begin{aligned}
\mu &= \left(\frac{W}{V_f}\right)\frac{(0.1667)^2}{(.3708)^3}\frac{0.004167}{(2\pi\times .3333)} \\
\mu &= \left(\frac{W}{V_f}\right)\left(\frac{0.02779}{0.05098}\right) \\
\mu &= \left(\frac{W}{V_f}\right)(1.085\times 10^{-3})\ \text{lbf}\cdot\text{s/ft}^2
\end{aligned}$$

Example: If $W = 2$oz. $= 0.125$lb. and V_f is measured to be 0.24 ft/s then

$$\begin{aligned}
\mu &= \frac{0.125}{0.24}(1.085\times 10^{-3})\ \text{lbf s/ ft}^2 \\
&= 0.564\times 10^{-4}\ \text{lbf}\cdot\text{ s/ ft}^2
\end{aligned}$$

REVIEW

Other things that could be noted or considered in the design:

1. Specify dimensions of all parts of the instrument.

2. Neglect friction in bearings of pulley and on shaft of cylinder.
3. Neglect weight of thread or monofilament line.
4. Consider degree of accuracy.
5. Estimate cost of the instrument.

2.69: PROBLEM DEFINITION

Situation:

Surface tension: (select all that apply)

a. only occurs at an interface, or surface
b. has dimensions of energy/area
c. has dimensions of force/area
d. has dimensions of force/length
e. depends on adhesion and cohesion
f. varies as a function of temperature

SOLUTION

Answers are a, b, d, e, and f.

Problem 2.70

(T/F) Hot water is better for washing clothes because (a) the surface tension of water decreases as temperature increases and (b) decreasing σ causes water to more readily soak into the clothing.

Feedback

Claim: The best choice is T.

Reasoning:

1. As $T \uparrow$, $\sigma \downarrow$; thus, (a) is true.
2. As $\sigma \downarrow$, water is better able to move into small pores; thus, (b) is true.

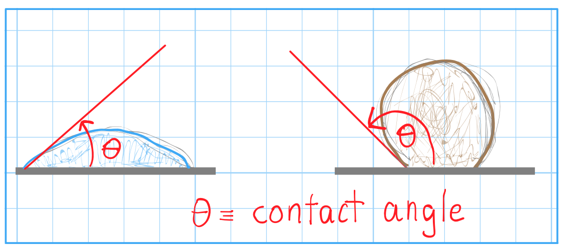
Problem 2.71

Consider a drop of water on a horizontal solid surface.

a. Sketch the drop on a hydrophobic surface and label the contact angle.
b. Sketch the drop on a hydrophilic surface and label the contact angle.
c. List three examples of hydrophobic surfaces.
d. List three examples of hydrophilic surfaces.

Feedback

A basic sketch follows.



Examples: hydrophobic surfaces

1. My car when I finish waxing it
2. Wax paper
3. My parka when it is new (the fabric has been treated)

Examples: hydrophilic surfaces

1. The palm of my hand
2. My car when I have not waxed it for a long time
3. The top of my desk

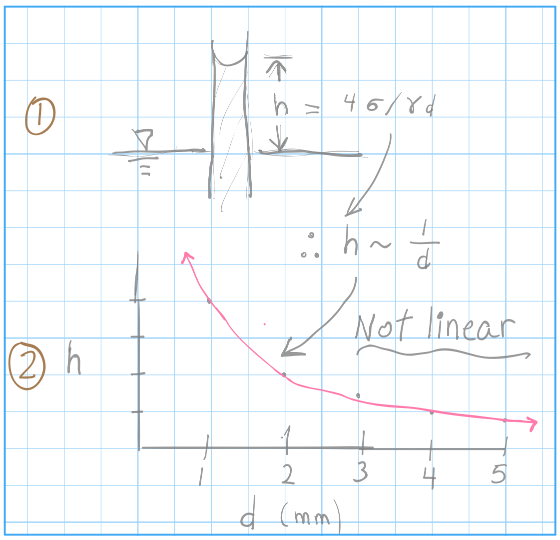
Problem 2.72

(T/F) A capillary tube is used in water. If the diameter of this tube decreases, then the capillary rise increases linearly.

Feedback

Claim: The best choice is F.

Reasoning:



The steps are:

1. Apply the capillary rise equation
2. Sketch h versus d
3. If $d\downarrow$, then $h\uparrow$, but the relationship is not linear

2.73: PROBLEM DEFINITION

Situation:

Very small spherical droplet of water.

Find:

Pressure inside.

SOLUTION

Refer to Example 2.4 (EFM12e). The surface tension force, $2\pi r\sigma$, will be resisted by the pressure force acting on the cut section of the spherical droplet or

$$\begin{aligned} p(\pi r^2) &= 2\pi r\sigma \\ p &= \frac{2\sigma}{r} \\ & \boxed{p = \frac{4\sigma}{d}} \end{aligned}$$

2.74: PROBLEM DEFINITION

Situation:

A spherical soap bubble.
Inside radius R, wall-thickness t, surface tension σ.
Special case: $R = 4\,\text{mm}$.

Find:

Derive a formula for the pressure difference across the bubble
Pressure difference for bubble with $R = 4\,\text{mm}$.

Assumptions:

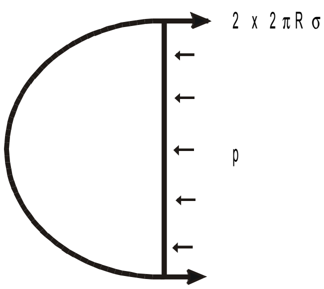
The effect of thickness is negligible, and the surface tension is that of pure water.

PLAN

Apply equilibrium, then the surface tension force equation.

SOLUTION

Force balance



Surface tension force

$$\begin{aligned} \sum F &= 0 \\ \Delta p \pi R^2 - 2(2\pi R\sigma) &= 0 \end{aligned}$$

Formula for pressure difference

$$\boxed{\Delta p = \frac{4\sigma}{R}}$$

Pressure difference

$$\Delta p_{\text{4mm rad.}} = \frac{4 \times 7.3 \times 10^{-2}\ \text{N/m}}{0.004\ \text{m}}$$

$$\boxed{\Delta p_{\text{4mm rad.}} = 73.0\ \text{N/m}^2}$$

2.75: PROBLEM DEFINITION

Situation:

A water bug is balanced on the surface of a water pond.
$n = 6$ legs, $\ell = 3\,\text{mm/leg}$.

Find:

Maximum mass of bug to avoid sinking.

Properties:

Surface tension of water, from Table A.4 (EFM12e), $\sigma = 0.073$ N/m.

PLAN

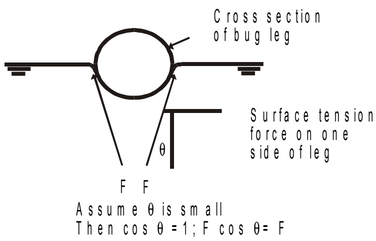
Apply equilibrium, then the surface tension force equation.

SOLUTION

Force equilibrium

$$\begin{aligned} \text{Upward force due to surface tension} &= \text{Weight of Bug} \\ F_T &= mg \end{aligned}$$

To find the force of surface tension (F_T), consider the cross section of one leg of the bug:



Surface tension force equation is given by $F_T = \sigma\ell$; here it is exerted on 2 sides of each leg.

$$\begin{aligned} F_T &= (2/\text{leg})(6\text{ legs})\sigma\ell \\ &= 12\sigma\ell \\ &= 12(0.073\text{ N/m})(0.003\text{ m}) \\ &= 0.00263\,\text{N} \end{aligned}$$

Apply equilibrium

$$\begin{aligned} F_T - mg &= 0 \\ m &= \frac{F_T}{g} = \frac{0.00263\,\text{N}}{9.81\,\text{m}^2/\text{s}} \\ &= 0.268 \times 10^{-3}\,\text{kg} \end{aligned}$$

$$\boxed{m = 0.268\,\mathrm{g}}$$

2.76: PROBLEM DEFINITION

Situation:

A water column in a glass tube is used to measure pressure.
$d_1 = 1/2\,\text{in}$, $d_2 = 1/8\,\text{in}$, $d_3 = 1/16\,\text{in}$.

Find:

Height of water column due to surface tension effects for all diameters.

Assumptions:
Assume that $\theta = 0$.

Properties:

From Table A.4 (EFM12e): surface tension of water is 0.005 lbf/ft.

SOLUTION

Surface tension force

$$
\begin{aligned}
\Delta h &= \frac{4\sigma}{\gamma d} = \frac{4 \times 0.005\,\text{lbf}/\,\text{ft}}{62.4\,\text{lbf}/\,\text{ft}^3 \times d\,\text{ft}} = \frac{3.21 \times 10^{-4}\,\text{ft}^2}{d\,\text{ft}} \\
d &= \frac{1}{2}\text{ in} = \frac{1}{24}\text{ ft; } \Delta h = \frac{3.21 \times 10^{-4}\,\text{ft}^2}{1/24\,\text{ft}} = 0.00769\text{ ft} = \boxed{0.0923\text{ in}} \\
d &= \frac{1}{8}\text{ in} = \frac{1}{96}\text{ ft; } \Delta h = \frac{3.21 \times 10^{-4}\,\text{ft}^2}{1/96\,\text{ft}} = 0.0308\text{ ft} = \boxed{0.369\text{ in}} \\
d &= \frac{1}{16}\text{ in} = \frac{1}{192}\text{ ft; } \Delta h = \frac{3.21 \times 10^{-4}\,\text{ft}^2}{1/192\,\text{ft}} = 0.0615\text{ ft} = \boxed{0.739\text{ in}}
\end{aligned}
$$

2.77: PROBLEM DEFINITION

Situation:

Two vertical glass plates

$t = 1\,\text{mm}$

Find:

Capillary rise (h) between the plates.

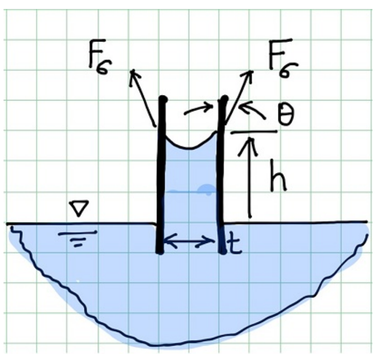
Properties:

From Table A.4 (EFM12e), surface tension of water is 7.3×10^{-2} N/m.

PLAN

Apply equilibrium, then the surface tension force equation.

SOLUTION



Equilibrium

$$\begin{aligned}
\sum F_y &= 0 \\
\text{Force due to surface tension} &= \text{Weight of fluid that has been pulled upward} \\
(2\ell)\,\sigma &= (h\ell t)\,\gamma
\end{aligned}$$

Solve for capillary rise (h)

$$\begin{aligned}
2\sigma\ell - h\ell t\gamma &= 0 \\
h &= \frac{2\sigma}{\gamma t} \\
h &= \frac{2 \times (7.3 \times 10^{-2}\,\text{N/m})}{9810\,\text{N/m}^3 \times 0.001\,\text{m}} \\
&= 0.0149\text{ m} \\
h &= \boxed{14.9\text{ mm}}
\end{aligned}$$

Problem 2.78

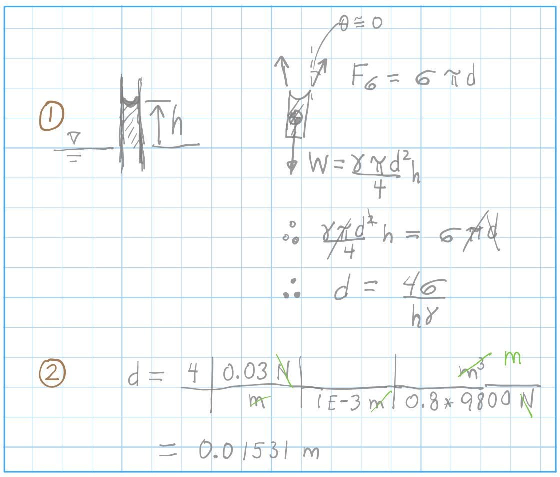
An engineer is designing a manometer. The capillary rise is limited to 1 mm. The fluid is kerosene. The parameters are $SG = 0.8$, and $\sigma = 0.03\,\mathrm{N/m}$.

In mm, what is the smallest diameter of tube that can be used? (a) 10 (b) 15 (c) 20 (d) 25 (e) 30

Feedback

Claim: The best choice is (b)

Reasoning: As $d \downarrow$, $h \uparrow$. Thus, solve for d that gives the specified capillary rise.



The steps are:

1. Derive the equation for capillary rise. Note: While this formula can be looked up, I usually derive a formula I need because this is faster for me than looking up the formula.
2. Do the calcs

2.79: PROBLEM DEFINITION

Situation:

A spherical water drop.

$d = 0.75\,\text{mm}$; therefore $R = 3.75 \times 10^{-4}\,\text{m}$

Find:

Pressure inside the droplet (N/m^2)

Properties:

From Table A.4 (EFM12e), surface tension of water is 7.3×10^{-2} N/m

PLAN

Apply equilibrium, then the surface tension force equation.

SOLUTION

Equilibrium (half the water droplet)

$$\begin{aligned} \text{Force due to pressure} &= \text{Force due to surface tension} \\ pA &= \sigma L \\ \Delta p \pi R^2 &= 2\pi R \sigma \end{aligned}$$

Solve for pressure

$$\begin{aligned} \Delta p &= \frac{2\sigma}{R} \\ \Delta p &= \frac{2 \times 7.3 \times 10^{-2}\,\text{N/m}}{(3.75 \times 10^{-4}\,\text{m})} \\ & \boxed{\Delta p = 389 \text{ N/m}^2} \end{aligned}$$

2.80: PROBLEM DEFINITION

Situation:

A tube employing capillary rise is used to measure temperature of water

$T_0 = 0\,^\circ\mathrm{C}$, $T_{100} = 100\,^\circ\mathrm{C}$

$\sigma_0 = 0.0756\,\mathrm{N/\,m}$, $\sigma_{100} = 0.0589\,\mathrm{N/\,m}$

Find:

Size the tube (this means specify diameter and length).

Assumptions:

Assume for this problem that differences in γ,due to temperature change, are negligible.

PLAN

Apply equilibrium and the surface tension force equation.

SOLUTION

The elevation in a column due to surface tension is

$$\Delta h = \frac{4\sigma}{\gamma d}$$

where γ is the specific weight and d is the tube diameter. For the change in surface tension due to temperature, the change in column elevation would be

$$\Delta h = \frac{4\Delta\sigma}{\gamma d} = \frac{4 \times 0.0167\,\mathrm{N/\,m}}{9810\,\mathrm{N/\,m^3} \times d} = \frac{6.8 \times 10^{-6}{}^2}{d\ \ \mathrm{m}}\ \mathrm{m}^2 = \frac{6.8\,\mathrm{mm}^2}{d\,\mathrm{mm}}$$

The change in column elevation for a $\boxed{\text{1-mm diameter}}$ tube would be $\boxed{\text{6.8 mm}}$. Special equipment, such the optical system from a microscope, would have to be used to measure such a small change in deflection It is unlikely that smaller tubes made of transparent material can be purchased to provide larger deflections.

2.81: PROBLEM DEFINITION

Situation:

Capillary rise is the distance water will rise above a water table, because the interconnected pores in the soil act like capillary tubes. This means that deep-rooted plants in the desert need only grow to the top of the "capillary fringe" in order to get water; they do not have to extend all the way down to the water table.

a. Assuming that interconnected pores can be represented as a continuous capillary tube, how high is the capillary rise in a soil consisting of a silty soil, with pore diameter of 10 μm?

b. Is the capillary rise higher in a soil with fine sand (pore d approx. 0.1 mm), or in fine gravel (pore d approx. 3 mm)?

c. Root cells extract water from soil using capillarity. For root cells to extract water from the capillary zone, do the pores in a root need to be smaller than, or greater than, the pores in the soil?

SOLUTION

a. Apply principals of surface tension, using Eq. 2.23 of EFM12e:

$$\Delta h = \frac{4\sigma}{\gamma d}$$

From Table A.5 in EFM12e, bottom line, $\sigma_{air/water} = 7.3\times10^{-2}\,\mathrm{N/\,m}$

$$\begin{aligned} \Delta h &= \left(\frac{4(7.3\times10^{-2})\,\mathrm{N}}{\mathrm{m}}\right)\left(\frac{\mathrm{m}^3}{9810\,\mathrm{N}}\right)\left(\frac{1}{10\times10^{-6}\,\mathrm{m}}\right) \\ & \boxed{\Delta h = 3.0\,\mathrm{m}} \end{aligned}$$

b. By inspection of Eq. 2.23 of EFM12e, the pore diameter, d, is in the denominator, so as d gets smaller, Δh increases. Therefore, capillary rise is higher in a clay than in a gravel, because the pores are smaller.

c. In order to "wick" water from the soil, the pores in the roots need to be smaller than the pores in the soil.

2.82: PROBLEM DEFINITION

Situation:

A soap bubble and a droplet of water of equal diameter in air

$d = 2\,\text{mm}$, $\sigma_{bubble} = \sigma_{droplet}$

Find:

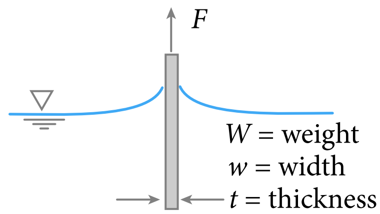
Which has the greater pressure inside.

SOLUTION

The soap bubble will have the greatest pressure because there are two surfaces (two surface tension forces) creating the pressure within the bubble. The correct choice is $\boxed{\text{a)}}$

Problem 2.83

Surface tension can be found by measuring the force to lift a plate:



If the buoyant force on the plate is neglected, the surface tension is given by $\sigma =$

a. $\dfrac{W+F}{(w+t)}$

b. $\dfrac{W}{Fwt}$

c. $\dfrac{W-F}{2wt}$

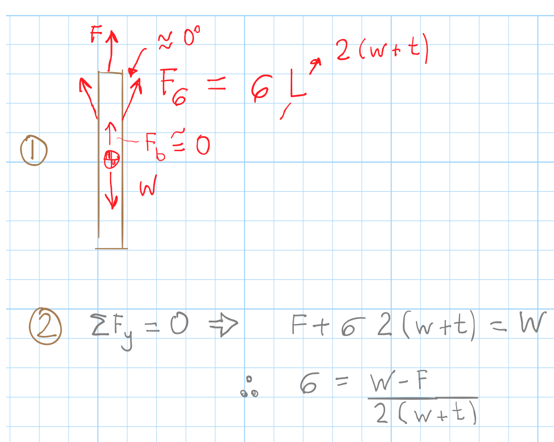
d. $\dfrac{W+F}{2wt}$

e. $\dfrac{W-F}{2(w+t)}$

Feedback

Claim: The best choice is (e)

Reasoning:



The steps are

1. Sketch a FBD of the plate.
2. Apply $\Sigma F_y = 0$

2.84: PROBLEM DEFINITION

Situation:

Surface tension is being measured by suspending liquid from a ring

$D_i = 10\,\text{cm},\ D_o = 9.5\,\text{cm}$

$m = 10\,\text{g},\ F = 16\,\text{g} \times g$, where g is the acceleration of gravity

Find:

Surface tension (N/ m)

PLAN

1. Force equilibrium on the fluid suspended in the ring. For force due to surface tension, use the form of the equation provided in the text for the special case of a ring being pulled out of a liquid.
2. Solve for surface tension - all the other forces are known.

SOLUTION

1. Force equilibrium

$$\begin{aligned} (\text{Upward force}) &= (\text{Weight of fluid}) + (\text{Force due to surface tension}) \\ F &= W + \sigma(\pi D_i + \pi D_o) \end{aligned}$$

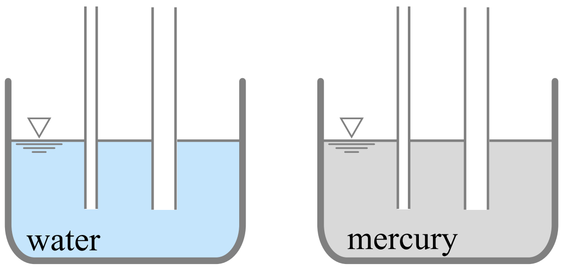
2. Solve for surface tension

$$\begin{aligned} \sigma &= \frac{F - W}{\pi(D_i + D_o)} \\ \sigma &= \frac{(0.016 - 0.010)\,\text{kg} \times 9.81\,\text{m/s}^2}{\pi(0.1 + 0.095)\,\text{m}} \\ \sigma &= 9.61 \times 10^{-2}\,\frac{\text{kg}}{\text{s}^2} \end{aligned}$$

$$\boxed{\sigma = 0.0961\ \text{N/m}}$$

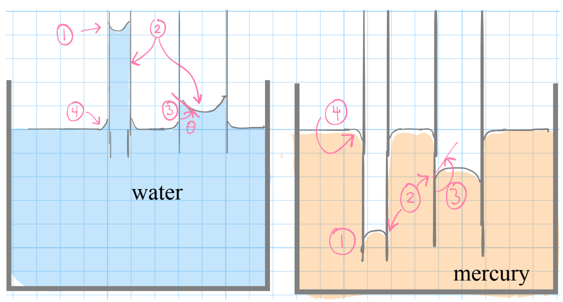
Problem 2.85

Sketch the capillary rise or depression in each of the four capillary tubes. Describe the significant feature of your completed sketch.



Feedback

A quick sketch follows:



In the water, the significant features are

1. Capillary rise
2. Greater rise in the small diameter tube
3. A contact angle less than 90°
4. The water is displaced upward on the tube

In the mercury, the significant features are

1. Capillary depression
2. Greater drop in the small diameter tube
3. A contact angle greater than 90°
4. The water is displaced downward on the tube

2.86: PROBLEM DEFINITION

Situation:

If liquid water at 30°C is flowing in a pipe and the pressure drops to the vapor pressure, what happens in the water?

a. the water begins condensing on the walls of the pipe
b. the water boils
c. the water flashes to vapor

SOLUTION

The answer is (b), it boils. Answer (c) is not correct. Flash vaporization is an industrial process used to separate volatile hydrocarbons; see the internet.

Problem 2.87

If a pot of water boils at 90 °C, what is the local atmospheric pressure in units of kPa absolute?

(a) 70 (b) 80 (c) 85 (d) 90 (e) 95

Feedback

Answer The best choice is (a)

Reasoning:

1. Water boils at its vapor pressure.
2. Table A.5 lists the vapor pressure for the given temperature as 70.1 kPa absolute.

2.88: PROBLEM DEFINITION

Situation:
$T = 30\,^\circ\mathrm{C}$,fluid is water.

Find:
The pressure that must be imposed to cause boiling

PLAN

Vapor pressure (P_v) is the pressure at which water boils for a given temperature.

SOLUTION

Bubbles will be noticed to be forming when $P = P_v$.
Consult Table A.5 (EFM12e) for $T = 30\,^\circ\mathrm{C}$.

$$\boxed{P = 4250 \text{ Pa abs}}$$

2.89: PROBLEM DEFINITION

Situation:

Water in a closed tank

$T = 20\,°\text{C}$, $p = 12,300\,\text{Pa abs}$

Find:

Whether water will bubble into the vapor phase (boil).

Properties:

From Table A.5 (EFM12e), at $T = 20\,°\text{C}$, $P_v = 2340$ Pa abs

SOLUTION

The tank pressure is 12,300 Pa abs, and $P_v = 2340$ Pa abs for $T = 20\,°\text{C}$.
So the tank pressure is higher than the P_v. Therefore the $\boxed{\text{water will not boil}}$.

REVIEW

The water can be made to boil at this temperature only if the pressure is reduced to 2340 Pa abs. Or, the water can be made to boil at this pressure only if the temperature is raised to $50\,°\text{C}$.

2.90: PROBLEM DEFINITION

Situation:

The boiling temperature of water decreases with increasing elevation
$\frac{\Delta p}{\Delta T} = \frac{-3.1\,\mathrm{kPa}}{^oC}$.

Find:

Boiling temperature at an altitude of 3000 m

Properties:

$T = 100^o\mathrm{C}$, $p = 101\,\mathrm{kN/\,m^2}$.
$z_{3000} = 3000\,\mathrm{m}$, $p_{3000} = 69\,\mathrm{kN/\,m^2}$.

Assumptions:

Assume that vapor pressure versus boiling temperature is a linear relationship.

PLAN

Develop a linear equation for boiling temperature as a function of elevation.

SOLUTION

Let BT = "Boiling Temperature." Then, BT as a function of elevation is

$$BT\ (3000\text{ m}) = BT\ (0\text{ m}) + \left(\frac{\Delta BT}{\Delta p}\right)\Delta p$$

Thus,

$$\begin{aligned} BT\ (3000\text{ m}) &= 100\,^\circ\mathrm{C} + \left(\frac{-1.0\,^\circ\mathrm{C}}{3.1\,\mathrm{kPa}}\right)(101-69)\text{ kPa} \\ BT\ (3000\text{ m}) &= 89.677\,^\circ\mathrm{C} \end{aligned}$$

$$\boxed{\text{Boiling Temperature } (3000\text{ m}) = 89.7\,^\circ\mathrm{C}}$$

Problem 2.91

Pressure cooking involves cooking food in a sealed container at a gage pressure between 0.7 bar and 1.0 bar. The main benefit of pressure cooking is faster cooking as compared to cooking on a stove top. Why is pressure cooking faster?

Feedback

Stove top cooking takes place at a pressure of about 1 bar absolute or less. Pressure cooking takes place at a pressure 1.7 to 2 bar absolute. Thus, water during conventional cooking can reach 100 °C and water during pressure cooking can reach as high as 120 °C. This higher water temperature cooks the food faster.