Chapter 2

Properties of Fluids

PROBLEM SELECTION GUIDE

Sec	Exer/Prob	Units	Difficulty	Length	Parts	Similar	Special features
2.3	*Density, Specific Weight, Specific Volume, and Specific Gravity*						
	X[1]2.3.1	BG	V Easy	V Short	1	2.3.2	
	2.3.2	SI	V Easy	V Short	1	2.3.1	
	2.3.3	BG	V Easy	V Short	1	2.3.4	
	2.3.4	SI	V Easy	V Short	1	2.3.3	
	2.3.5	SI	V Easy	V Short	1	P2.2	
	2.3.6	B	V Easy	V Short	1		
	2.3.7	BG	Easy	V Short	1	P2.3	
	P 2.1	SI	V Easy	V Short	1		
	2.2	BG	V Easy	V Short	1	X2.3.5	
	2.3	SI	Easy	V Short	1	X2.3.7	
	2.4	BG	Easy	Medium	3		
	2.5	SI	Medium	Short	1		
2.5	*Compressibility of Liquids*						
	X 2.5.1	B	Easy	V Short	2		2-D interpolation; unit conversions
	2.5.2	BG	Easy	V Short	1	2.5.4	
	2.5.3	BG	Easy	V Short	1		
	2.5.4	SI	Easy	V Short	1	2.5.2	
	2.5.5	SI	Easy	Short	1	P2.7	
	P 2.6	BG	Easy	Short	5		
	2.7	BG	Easy	Short	1	X2.5.5	
	2.8	SI	Medium	Medium	3		Interpolation in 2 directions
2.6	*Specific Weight of Liquids*						
	X 2.6.1	B	V Easy	V Short	2	2.6.2	†
	2.6.2	B	V Easy	V Short	2	2.6.1	†
	2.6.3	BG	Easy	Short	1		
	2.6.4	SI	Easy	Short	1		
	P 2.9	BG	Medium	Short	1		† Interpolation
	2.10	SI	Medium	Medium	1		

/cont...

[1] For all Exercises (identifed by "X"), answers are given in Appendix F of the textbook.
† Answers are sensitive to values that are read from graphs.
X = Exercise, P = (end-of-chapter) Problem, S = Sample Problem.

Sec	Exer/Prob	Units	Difficulty	Length	Parts	Similar	Special features
2.7	***Property Relations for Perfect Gases***						
	X 2.7.1	SI	Easy	V Short	1		
	2.7.2	BG	Easy	V Short	1		
	2.7.3	BG	Easy	Short	1	2.7.4	
	2.7.4	SI	Easy	Short	1	2.7.3	
	2.7.5	BG	Easy	Short	1		
	2.7.6	BG	Easy	Short	1		Partial pressures
	2.7.7	N	Medium	Short	1		Derivation
	P 2.11	SI	Easy	Short	2		
	2.12	BG	Easy	Short	3	2.13	
	2.13	SI	Easy	Short	3	2.12	
	2.14	BG	Easy	Short	3		Partial pressures
	2.15	SI	Medium	Medium	3		Partial pressures
	2.16	BG	Medium	Medium	5		Partial pressures
2.8	***Compressibility of Gases***						
	X 2.8.1	BG	V Easy	V Short	1	2.8.2	
	2.8.2	SI	V Easy	V Short	1	2.8.1	
	2.8.3	SI	Easy	Short	2		
	2.8.4	BG	Medium	Short	1	P2.19	
	P 2.17	BG	Easy	Short	2	2.18	
	2.18	SI	Easy	Short	2	2.17	
	2.19	SI	Medium	Short	1	X2.8.4	
2.11	***Viscosity***						
	X 2.11.1	B	V Easy	V Short	1		† Unit conversions (minor)
	2.11.2	BG	V Easy	V Short	1		†
	2.11.3	BG	V Easy	V Short	1		
	2.11.4	SI	Easy	V Short	1	2.11.5	
	2.11.5	BG	Easy	V Short	1	2.11.4	
	2.11.6	B	Easy	Short	1		Unit conversions
	2.11.7	B	Easy	Short	3		†
	2.11.8	SI	Easy	Short	2		†
	2.11.9	B	Easy	Short	1	P2.23	† Unit conversions
	2.11.10	N	Easy	Short	1		Integration
	2.11.11	BG	Easy	Medium	1		Unit conversion (minor)
	2.11.12						
	P 2.20	SI	Medium	Short	1		Unit conversion (minor)
	2.21	BG	Medium	Short	1	2.22	
	2.22	SI	Medium	Short	1	2.21	
	2.23	BG	Medium	Short	1	X2.11.9	†
	2.24	BG	Hard	Medium	1		† Integration
	2.25	SI	Medium	Short	1		Integration
	2.26	N	Hard	Medium	1		Integration
	2.27	SI			2		
	2.28	SI			3		

/cont...

Sec	Exer/Prob	Units	Difficulty	Length	Parts	Similar	Special features
2.12	*Surface Tension*						
	X 2.12.1	BG	V Easy	V Short	1	2.12.2	†
	2.12.2	SI	Easy	V Short	1	2.12.1	†
	2.12.3	BG	V Easy	V Short	1		
	2.12.4	SI	Easy	V Short	1		
	2.12.5	BG	Easy	Short	1		† Interpolation
	P 2.29	BG	Easy	Short	1		
	2.30	SI	Easy	Short	1		
	2.31	SI	Medium	Short	1	2.32	
	2.32	BG	Medium	Short	1	2.31	
2.13	*Vapor Pressure of Liquids*						
	X 2.13.1	SI	V Easy	V Short	1		
	2.13.2	BG	Easy	Short	1	P2.34	Interpolation twice
	P 2.33	BG	V Easy	V Short	1		
	2.34	SI	Easy	Short	1	X2.13.2	Interpolation twice

Chapter 2
PROPERTIES OF FLUIDS

Sec. 2.3: Density, Specific Weight, Specific Volume, and Specific Gravity – *Exercises* (7)

2.3.1 BG *If the specific weight of a liquid is 52 lb/ft³, what is its density?*

Eq. 2.1: $\rho = 52/32.2 = 1.615$ slugs/ft³ ◀

2.3.2 SI *If the specific weight of a liquid is 8.1 kN/m³, what is its density?*

Eq. 2.1: $\rho = 8100/9.81 = 826$ kg/m³ ◀

2.3.3 BG *If the specific volume of a gas is 375 ft³/slug, what is its specific weight in lb/ft³?*

Eqs. 2.1, 2.2: $\gamma = \rho g = \dfrac{g}{v} = \dfrac{32.2\ \text{ft/sec}^2}{375\ \text{ft}^3\text{/slug}}\left(\dfrac{\text{lb}}{\text{slug}\cdot\text{ft/sec}^2}\right) = 0.0859\ \text{lb/ft}^3$ ◀

2.3.4 SI *If the specific volume of a gas is 0.70 m³/kg, what is its specific weight in N/m³?*

Eqs. 2.1, 2.2: $\gamma = \rho g = \dfrac{g}{v} = \dfrac{9.81\ \text{m/s}^2}{0.70\ \text{m}^3\text{/kg}}\left(\dfrac{\text{N}}{\text{kg}\cdot\text{m/s}^2}\right) = 14.01\ \text{N/m}^3$ ◀

2.3.5 SI *A certain gas weighs 16.0 N/m³ at a certain temperature and pressure. What are the values of its density, specific volume, and specific gravity relative to air weighing 12.0 N/m³?*

Eq. 2.1: $\rho = 16/9.81 = 1.631$ kg/m³ ◀

Eq. 2.2: $v = 1/1.631 = 0.613$ m³/kg ◀

$s = 16/12 = 1.333$ ◀

2.3.6 B *The specific weight of glycerin is 78.6 lb/ft³. Compute its density and specific gravity. What is its specific weight in kN/m³?*

Eq. 2.1: $\rho = 78.6/32.2 = 2.44$ slugs/ft³ ◀

$s = 78.6/62.4 = 1.260$ ◀ so $\rho = 1.260$ Mg/m³

Eq. 2.1: $\gamma = 9.81(1.260) = 12.36$ kN/m³ ◀

2.3.7 BG *If a certain gasoline weights 43 lb/ft³, what are the values of its density, specific volume, and specific gravity relative to water at 60°F? Use Appendix A.*

Eq 2.1: $\rho = 43/32.2 = 1.335$ slugs/ft³ ◀

Eq 2.2: $v = 1/1.335 = 0.749$ ft³/slug ◀

Table A.1: ρ_{water} at 60°F = 1.938 slugs/ft³; $s = 1.335/1.938 = 0.689$ ◀

Sec 2.3: Density, Specific Weight, Specific Volume, and Specific Gravity -- ***Problems** 2.1–2.5*

2.1 *If the specific weight of a gas is 12.40 N/m³, what is its specific volume in m³/kg?*

SI

Eq. 2.2: $$v = \frac{1}{\rho} = \frac{g}{\gamma} = \frac{9.81\ \text{m/s}^2}{12.40(\text{kg}\cdot\text{m/s}^2)/\text{m}^3} = 0.791\ \text{m}^3/\text{kg} \quad ◄$$

2.2 *A gas sample weighs 0.108 lb/ft³ at a certain temperature and pressure. What are the values of its density, specific volume, and specific gravity relative to air weighing 0.075 lb/ft³?*

BG

Eq. 2.1: $\rho = 0.108/32.2 = 0.003\,35\ \text{slugs/ft}^3$ ◄

Eq. 2.2: $v = 1/0.003\,35 = 298\ \text{ft}^3/\text{slug}$ ◄ $\quad s = 0.108/0.075 = 1.440$ ◄

2.3 *If a certain liquid weighs 8600 N/m³, what are the values of its density, specific volume, and specific gravity relative to water at 15°C? Use Appendix A.*

SI

Eq. 2.1: $\rho = 8600/9.81 = 877\ \text{kg/m}^3$ ◄ Eq. 2.2: $v = 1/877 = 0.001\ 141\ \text{m}^3/\text{kg}$ ◄

Table A.1: ρ_{water} at 15°C = 999.1 kg/m³ ; $s = 877/999.1 = 0.877$ ◄

2.4 *Find the change in volume of 15.00 lb of water at ordinary atmospheric pressure for the following conditions: (a) reducing the temperature by 50°F from 200°F to 150°F, (b) reducing the temperature by 50°F from 150°F to 100°F, and (c) reducing the temperature by 50°F from 100°F to 50°F. Calculate each and note the trend in the changes in volume.*

BG

$W = \gamma\mathcal{V}$, so $\mathcal{V} = W/\gamma = 12.00/\gamma$

T °F	γ (Table A.1) lb/ft³	$\mathcal{V} = 15.00/\gamma$ ft³
200	60.12	0.249 501
150	61.20	0.245 098
100	62.00	0.241 935
50	62.41	0.240 346

(*a*) $\Delta\mathcal{V}_{200\,-\,150} = 0.004\ 40\ \text{ft}^3$ decrease in volume ◄

(*b*) $\Delta\mathcal{V}_{150\,-\,100} = 0.003\ 16\ \text{ft}^3$ decrease in volume ◄

(*c*) $\Delta\mathcal{V}_{100\,-\,50} = 0.001\ 589\ \text{ft}^3$ decrease in volume ◄

For $\Delta T = 50°$ F, the volume change increases with temperature ◄

2.5 *Initially when 1000.00 mL of water at 10°C are poured into a glass cylinder the height of the water column is 1000.0 mm. The water and its container are heated to 70°C. Assuming no evaporation, what then will be the depth of the water column if the coefficient of thermal expansion for the glass is 3.8×10⁻⁶ mm/mm per °C?*

SI

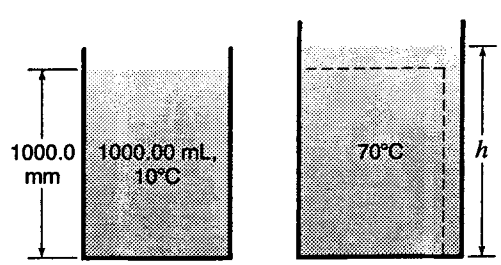


Figure P2.5

Table A.1 for water at 10°C: $\rho = 999.7\ \text{kg/m}^3$;

for water at 70°C: $\rho = 977.8\ \text{kg/m}^3$.

Mass of water = $\rho\mathcal{V} = \rho_{10}\mathcal{V}_{10} = \rho_{70}\mathcal{V}_{70}$

$(999.7\ \text{kg/m}^3)(1000.0\ \text{mL}) = (977.8\ \text{kg/m}^3)\mathcal{V}_{70}$; so $\mathcal{V}_{70} = 1022.40\ \text{mL} = 1022\ 400\ \text{mm}^3$

$A_{10} = \mathcal{V}_{10}/h_{10} = 1000\,000.00\ \text{mm}^3/1000.0\ \text{mm} = 1000.0\ \text{mm}^2$

$$A_{70} = A_{10}[1 + (70 - 10)3.8 \times 10^{-6}]^2 = 1000.5\ \text{mm}^2\ ; \qquad h_{70} = \frac{\mathcal{V}_{70}}{A_{70}} = \frac{1022\,400}{1000.5} = 1021.9\ \text{mm} \quad ◄$$

Sec. 2.5: Compressibility of Liquids – *Exercises (5)*

2.5.1 *To two significant figures what is the bulk modulus of water in MN/m² at 50°C under a pressure of 30 MN/m²? Use Table 2.1.*

B

From inside cover: 50°C = 122°F; 30 MN/m² = 4351 psi

From Table 2.1, by linear interpolation in two directions: $E_v \approx 360{,}400$ psi

$E_v \approx 360{,}400(6895/10^6) = 2485\ \text{MN/m}^2 \approx 2500\ \text{MN/m}^2$ ◀

2.5.2 *At normal atmospheric conditions, approximately what pressure in psi must be applied to water to reduce its volume by 2% ? Use Table 2.1.*

BG

Table 2.1: At normal atmospheric conditions, $E_v \approx 320{,}000$ psi

From Eq. 2.3*a*: $\Delta v/v_1 = -0.02 = -\Delta p/320{,}000$; $\Delta p = 6400$ psi ◀

2.5.3 *Water in a hydraulic press is subjected to a pressure of 4500 psia at 68°F. If the initial pressure is 15 psia, approximately what will be the percentage decrease in specific volume? Use Table 2.1*

BG

From Table 2.1: $E_v \approx (320{,}000 + 348{,}000)/2 = 334{,}000$ psi

Eq. 2.3: $\dfrac{\Delta v}{v_1} = \dfrac{-(4500-15)}{365{,}000} = -0.013\,43$ or 1.34% decrease ◀

2.5.4 *At normal atmospheric conditions, approximately what pressure in MPa must be applied to water to reduce its volume by 3% ?*

SI

Table 2.1: At normal atmospheric conditions, $E_v \approx 320{,}000$ psi

$E_v \approx (320{,}000\ \text{psi})(6895) = 2.21\times10^9\ \text{Pa} = 2210\ \text{MPa}$

From Eq. 2.3*a*: $\dfrac{\Delta v}{v_1} = -0.03 = \dfrac{-\Delta p}{2210}$; $\Delta p = 66.2$ MPa ◀

2.5.5 *A rigid cylinder, inside diameter 15 mm, contains a column of water 500 mm long. What will the column length be if a force of 2 kN is applied to its end by a frictionless plunger? Assume no leakage.*

SI

$p_1 = 0;\ p_2 = \dfrac{\text{Force}}{\text{Area}} = \dfrac{2\ \text{kN}}{\pi(0.0075\ \text{m})^2}$

$= 11\,320\ \text{kN/m}^2 = 11.32\ \text{MPa}$

$E_v \approx 320{,}000\ \text{psi}(6895) = 2.21\times10^9\ \text{Pa} = 2210\ \text{MPa}$

Since the tube is rigid, using Eq. 2.3*b*:

$$\frac{v_2 - v_1}{v_1} = \frac{L_2 - L_1}{L_1} \approx \frac{-(p_2 - p_1)}{E_v}$$

so $L_2 - 0.5 \approx -(0.5\ \text{m})\dfrac{11.32 - 0}{2210} = -0.00256$ m

$L_2 \approx 0.5 - 0.00256 = 0.497$ m or 497 mm ◀

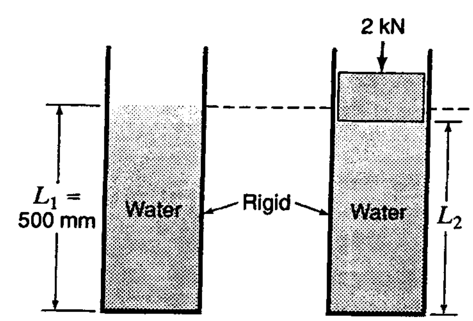


Figure X2.5.5

Sec. 2.5: Compressibility of Liquids -- *Problems* 2.6–2.8

2.6 *At a depth of 4 miles in the ocean the pressure is 9,520 psi. Assume specific weight at the surface is 64.00 lb/ft³ and that the average volume modulus is 320,000 psi for that pressure range. (a) What will be the change in specific volume between that at the surface and at that depth? (b) What will be the specific volume at that depth? (c) What will be the specific weight at that depth? (d) What is the percentage change in the specific volume? (e) What is the percentage change in the specific weight?*

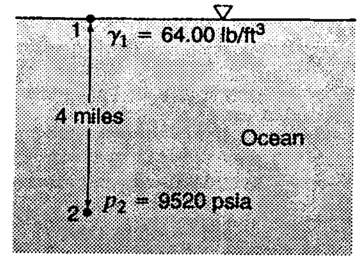


Figure P2.6

BG

(*a*) $v_1 = 1/\rho_1 = g/\gamma_1 = 32.2/64.00 = 0.503$ ft³/slug

Eq. 2.3: $\Delta v = \dfrac{-0.503(9520 - 0)}{320{,}000} = -0.014\,97$ ft³/slug ◀

(*b*) From Eq. 2.3: $v_2 = v_1 + \Delta v = 0.503 - 0.014\,97 = 0.488$ ft³/slug ◀

(*c*) $\gamma_2 = g/v_2 = 32.2/0.488 = 66.0$ lb/ft³ ◀

(*d*) $\Delta v/v_1 = 0.014\,97/0.503 = 2.98\%$ decrease ◀

(*e*) $\Delta\gamma/\gamma_1 = (66.0 - 64.00)/64.00 = 3.07\%$ increase ◀

2.7 *Water at 68°F is in a long rigid cylinder of inside diameter 0.600 in. A plunger applies pressure to the water. If, with zero force, the initial length of the column of water is 25.00 in, what will be its length be if a force of 420 lb is applied to the plunger. Assume no leakage and no friction.*

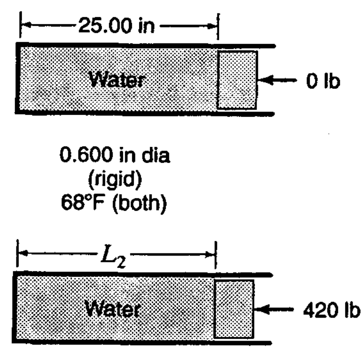


Figure P2.7

BG

$p_1 = 0$ psi gage $= 14.7$ psia

$p_2 =$ Force/Area $= 420/\pi(0.300)^2 = 1485$ lb/in² gage $= 1500$ psia

Since the tube is rigid, from Eq. 2.3:

$$\Delta v/v = \Delta L/L = (L_2 - L_1)/L_1 = -(p_2 - p_1)/E_v$$

Table 2.1 at 68°F: $(E_v)_1 = 320{,}000$ psi, $(E_v)_2 = 330{,}000$ psi,

∴ average for the range = 325,000 psi.

So $L_2 - 25.00 = -25.00(1485 - 0)/325{,}000 = -0.1143$ in ; $L_2 = 25.00 - 0.1143 = 24.9$ in ◀

2.8 *Find the change in volume of 10.00 m³ of water for the following situations: (a) a temperature increase from 60°C to 70°C with constant atmospheric pressure, (b) a pressure increase from zero to 10 MN/m² with temperature remaining constant at 60°C, and (c) a temperature decrease from 60°C to 50°C combined with a pressure increase from zero to 10 MN/m².*

SI

(*a*) Table A.1 (atmospheric pressure): $\gamma_{60} = 9.642$ kN/m³, $\gamma_{70} = 9.589$ kN/m³

$W = \gamma\mathcal{V} = \gamma_{60}\mathcal{V}_{60} = \gamma_{70}\mathcal{V}_{70}$ so $9.642(10) = 9.589\mathcal{V}_{70}$, from which $\mathcal{V}_{70} = 10.055\,3$ m³

$\Delta\mathcal{V}_{70-60} = 10.055\,3 - 10.000\,0 = 0.055\,3$ m³ increase in volume ◀

(*b*) 10 MN/m² ≡ $10 \times 10^6/6894 = 1450$ psi ; 60°C ≡ 32 + (9/5)60 = 140° F

From Table 2.1, by linear interpolation in 2 directions, for 140°F, 740 psia: $E_v = 331{,}400$ psi

$E_v \equiv 331{,}400(6895) = 2.28 \times 10^9$ Pa $= 2280$ MN/m²

Letting the constant mass of water be m, then $m = \rho\mathcal{V}$ and so $1/\rho = \mathcal{V}/m$

But from Eq. 2.2: $v = 1/\rho$ so $v = \mathcal{V}/m$

/cont...

Using this relation to substitute for v into Eq. 2.3, remembering that m is constant:

$(v_2 - v_1)/v_1 = (\mathcal{V}_2 - \mathcal{V}_1)/\mathcal{V}_1 = -\Delta p/E_v$

So $\Delta\mathcal{V} = -\mathcal{V}\Delta p/E_v = -(10.00 \text{ m}^3)10/2280 = -0.043\,8 \text{ m}^3$ ◄

The minus sign indicates a reduction in volume.

(*c*) Table A.1: $\gamma_{60} = 9.642 \text{ kN/m}^3$, $\gamma_{50} = 9.689 \text{ kN/m}^3$. $55°\text{C} = 131°\text{F}$.

Constant weight $= \gamma_{60}\mathcal{V}_{60} = \gamma_{50}\mathcal{V}_{50}$ so $9.642(10) = 9.689V_{50}$ from which $\mathcal{V}_{50} = 9.95 \text{ m}^3$

So due to temperature decrease, $\Delta\mathcal{V}_{50-60} = -0.048\,5 \text{ m}^3$ (decrease).

From Table 2.1, by linear interpolation in 2 directions, for 131°F, 740 psia: $E_v = 334{,}100$ psi

$E_v \equiv 334{,}100(6895) = 2.30 \times 10^9 \text{ Pa} = 2300 \text{ MN/m}^2$

From Eq. 2.3: $\Delta\mathcal{V} = -\mathcal{V}_1\Delta p/E_v = -10(10/2300) = -0.043\,4 \text{ m}^3$ (decrease)

Summing the changes for both causes: $\Delta\mathcal{V} = 0.048\,5 + 0.043\,4 = 0.091\,9 \text{ m}^3$ (decrease) ◄

Sec. 2.6: Specific Weight of Liquids -- *Exercises (4)*

2.6.1 *Use Fig. 2.1 to find the approximate specific weight of water in lb/ft³ under the following conditions: (a) at a temperature of 60°C under 101.4 kPa abs pressure; (b) at 60°C under a pressure of 13.79 MPa abs.*

B

(*a*) From Fig. 2.1 at 60°C: At 101.3 kPa abs, $\gamma \approx 61.4$ pcf ◄

(*b*) At 13.79 MPa abs, $\gamma \approx 61.8$ pcf ◄

2.6.2 *Use Fig. 2.1 to find the approximate specific weight of water in kN/m³ under the following conditions: (a) at a temperature of 160°F under normal atmospheric pressure; (b) at 160°F under a pressure of 2000 psia.*

B

(*a*) From Fig. 2.1 at 160°F: At 14.7 psia, $\gamma \approx 9.59 \text{ kN/m}^3$ ◄

(*b*) At 2000 psia, $\gamma \approx 9.65 \text{ kN/m}^3$ ◄

2.6.3 *A vessel contains 5.0 ft³ of water at 40°F and atmospheric pressure. If the water is heated to 80°F what will be the percentage change in its volume? What weight of water must be removed to maintain the volume at its original value? Use Appendix A.*

BG

Table A.1: $\gamma_{40} = 62.43$ pcf, $\gamma_{80} = 62.22$ pcf

Weight of water $= \gamma\mathcal{V} = \gamma_{40}\mathcal{V}_{40} = \gamma_{80}\mathcal{V}_{80}$; $62.43(5) = 62.22\mathcal{V}_{80}$; $\mathcal{V}_{80} = 5.016\,88 \text{ ft}^3$

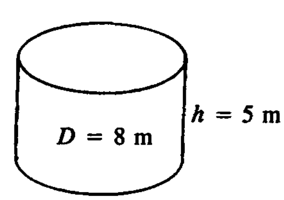
$$\frac{\Delta\mathcal{V}}{\mathcal{V}_{40}} = \frac{0.016\,88}{5} = 0.338\% \text{ increase}$$ ◄

Must remove $(0.016\,88 \text{ ft}^3)(62.22 \text{ lb/ft}^3) = 1.050$ lb ◄

2.6.4 *A cylindrical tank (diameter = 8.00 m and depth = 5.00 m) contains water at 15°C and is brimful. If the water is heated to 60°C, how much water will spill over the edge of the tank? Assume the tank does not expand with the change in temperature. Use Appendix A.*

SI

Table A.1: $\gamma_{15} = 9.798 \text{ kN/m}^3$, $\gamma_{60} = 9.642 \text{ kN/m}^3$



Tank vol $= \mathcal{V}_{15} = \pi 4^2(5) = 251.33 \text{ m}^3$

Weight of water in tank $= 9.798(251.33) = 2463$ kN

$\mathcal{V}_{60} = 2463/9.642 = 255.39 \text{ m}^3$; $\Delta\mathcal{V} = 255.39 - 251.33 = 4.07 \text{ m}^3$ ◄

Sec. 2.6: Specific Weight of Liquids -- *Problems 2.9–2.10*

2.9 *A heavy closed steel chamber is filled with water at 40°F and at atmospheric pressure. If the temperature of the water and the chamber is raised to 80°F, what will be the new pressure of the water? The coefficient of thermal expansion of the steel is 6.6 × 10^{-6} in/in per °F; Assume the chamber is unaffected by the water pressure. Use Table A.1 and Fig. 2.1.*

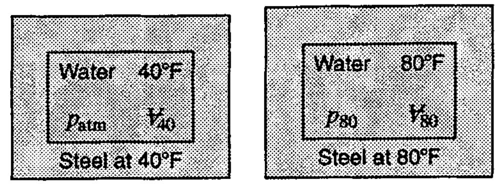


Figure P2.9

BG

$\mathcal{V}_{80} = \mathcal{V}_{40}[1 + (80 - 40)6.6 \times 10^{-6}]^3 = 1.000\,792\mathcal{V}_{40}$

Table A.1: $\gamma_{40} = 62.43$ lb/ft^3 at p = atmos.

Wt of water $= \gamma\mathcal{V} = \gamma_{40}\mathcal{V}_{40} = \gamma_{80}\mathcal{V}_{80}$; $62.43\mathcal{V}_{40} = \gamma_{80}(1.000\,792\mathcal{V}_{40})$; $\gamma_{80} = 62.38$ pcf

Fig. 2.1 for $\gamma = 62.38$ pcf, by linear interpolation: $p_{80} \approx 882$ psia ◄

2.10 *Repeat Exer. 2.6.4 for the case where the tank is made of a material which has a coefficient of thermal expansion of 4.6 × 10^{-6} mm/mm per °C.*

Exer. 2.6.4: A cylindrical tank (diameter = 8.00 m and depth = 5.00 m) contains water at 15°C and is brimful. If the water is heated to 60°C, how much water will spill over the edge of the tank? Use Appendix A.

SI

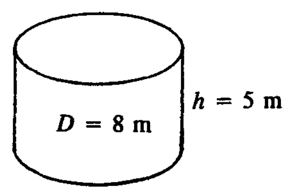


Table A.1: $\gamma_{15} = 9.798$ kN/m^3, $\gamma_{60} = 9.642$ kN/m^3

At 15°C, $\mathcal{V}_{\text{tank}} = \pi 4^2(5) = 251.33$ m^3; $\Delta T = 60 - 15 = 45°$ C

At 60°C, $\mathcal{V}_{\text{tank}} = 251.33[1 + (\Delta T)4.6 \times 10^{-6}]^3 = 251.33(1.000\,621)$

$\Delta\mathcal{V}_{\text{tank}} = 251.33(0.000\,621) = 0.1561$ m^3 increase

Weight of water $= \gamma\mathcal{V} = \gamma_{15}\mathcal{V}_{15} = \gamma_{60}\mathcal{V}_{60}$; $9.798(251.33) = 9.642\mathcal{V}_{60}$ from which $\mathcal{V}_{60} = 255.39$ m^3

$\Delta\mathcal{V}_{\text{water}} = 255.39 - 251.33 = 4.07$ m^3 increase ; spill $\Delta\mathcal{V} = 4.07 - 0.1561 = 3.91$ m^3 ◄

Sec. 2.7: Property Relations for Perfect Gases -- *Exercises (7)*

2.7.1 *A gas at 60°C under a pressure of 10 000 mb abs has a specific weight of 99 N/m^3. What is the value of R for the gas? What gas might this be? Refer to Appendix A, Table A.5.*

SI

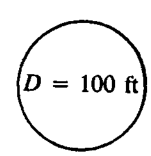
Eq. 2.5: $$R = \frac{gp}{\gamma T} = \frac{9.81 \text{ m/s}^2(10\,000 \times 100 \text{ N/m}^2)}{99 \text{ N/m}^3(273+60)\text{K}} = 298 \text{ m}^2/(\text{s}^2\cdot\text{K})$$ ◄

Table A.5: This gas with $R = 298$ might be carbon monoxide or nitrogen. ◄

2.7.2 *A hydrogen-filled balloon of the type used in cosmic-ray studies is to be expanded to its full size, which is a 100-ft-diameter sphere, without stress in the wall at an altitude of 150,000 ft. If the pressure and temperature at this altitude are 0.14 psia and −67°F respectively, find the volume of hydrogen at 14.7 psia and 60°F which should be added on the ground. Neglect the balloon's weight.*

BG

Eq. 2.4: $pv = RT$; $v = \mathcal{V}/m = \mathcal{V}g/W$; $\therefore$ $p\mathcal{V}g/W = RT$; $\therefore$ $p\mathcal{V}/T$ = constant



$$\frac{14.7\mathcal{V}_1}{460 + 60} = \frac{0.14 \times (4/3)\pi 50^3}{460 - 67}; \quad \mathcal{V}_1 = 6600 \text{ ft}^3$$ ◄

2.7.3 BG *Calculate the density, specific weight, and specific volume of air at 120°F and 50 psia.*

Eq. 2.5: $\gamma = \dfrac{gp}{RT} = \dfrac{32.2(50 \times 144)}{1715(460+120)} = 0.233 \text{ lb/ft}^3$ ◀

Eq. 2.1: $\rho = \gamma/g = 0.233/32.2 = 0.007\,24 \text{ slugs/ft}^3$ ◀

Eq. 2.2: $v = 1/\rho = 138.2 \text{ ft}^3\text{/slug}$ ◀

2.7.4 SI *Calculate the density, specific weight, and specific volume of air at 50°C and 3400 mb abs.*

Eq. 2.5: $\gamma = \dfrac{gp}{RT} = \dfrac{9.81(3400 \times 100)}{287(273+50)} = 36.0 \text{ N/m}^3$ ◀

Eq. 2.1: $\rho = \gamma/g = 36.0/9.81 = 3.67 \text{ kg/m}^3$ ◀

Eq. 2.2: $v = 1/\rho = 0.273 \text{ m}^3\text{/kg}$ ◀

2.7.5 BG *If natural gas has a specific gravity of 0.6 relative to air at 14.7 psia and 68°F, what are its specific weight and specific volume at that same pressure and temperature. What is the value of R for the gas? Solve without using Table A.2.*

Table A.5 for air: $R = 1715$ ft·lb/(slug·°R). Eq. 2.5: $\gamma_{air} = \dfrac{gp}{RT} = \dfrac{32.2(14.7)144}{1715(460+68)} = 0.0753 \text{ lb/ft}^3$

Sec. 2.3: $\gamma_{ngas} = s(\gamma_{air}) = 0.6(0.0753) = 0.0452 \text{ lb/ft}^3$ ◀

Eqs. 2.1 and 2.2: $v = 1/\rho = g/\gamma = 32.2/0.0452 = 713 \text{ ft}^3\text{/slug}$ ◀

Eq. 2.5: For a given T and p, gp/T is constant

$\therefore\ \gamma R = \gamma_{air}R_{air} = \gamma_{ngas}R_{ngas}$ and $R_{ngas} = R_{air}(\gamma_{air}/\gamma_{ngas}) = R_{air}/s_{ngas}$

or $R_{ngas} = 1715/0.6 = 2858$ ft·lb/(slug·°R) ◀

2.7.6 BG *Given that a sample of dry air at 40°F and 14.7 psia contains 21% oxygen and 78% nitrogen by volume. What is the partial pressure (psia) and specific weight of each gas?*

Table A.5: R(oxygen) = 1554 ft²/(sec²·°R); R(nitrogen) = 1773 ft²/(sec²·°R).

From Dalton's law, for O_2: $p = 0.21(14.7) = 3.09$ psia ◀

Eq. 2.5 for 21% O_2: $\gamma = 0.21\dfrac{(32.2 \text{ ft/sec}^2)(14.7 \times 144 \text{ lb/ft}^2)}{[1554 \text{ ft}^2/(\text{sec}^2\cdot°\text{R})](460+40)°\text{R}} = 0.018\,42 \text{ lb/ft}^3$ ◀

From Dalton's law, for N_2: $p = 0.78(14.7) = 11.47$ psia ◀

Eq. 2.5 for 78% N_2: $\gamma = 0.78\dfrac{(32.2)(14.7 \times 144)}{1773(500)} = 0.060\,0 \text{ lb/ft}^3$ ◀

2.7.7 N *Prove that Eq (2.7) follows from Eqs (2.4) and (2.6).*

Eq. 2.4: $v = RT/p$; Eq. 2.6: $p_1 v_1^n = p_2 v_2^n$

Eliminate v: $p_1\left(\dfrac{R_1T_1}{p_1}\right)^n = p_2\left(\dfrac{R_2T_2}{p_2}\right)^n$; but $R_1 = R_2$

Thus $\dfrac{T_1^n}{p_1^{n-1}} = \dfrac{T_2^n}{p_2^{n-1}}$ or $\left(\dfrac{T_2}{T_1}\right)^n = \left(\dfrac{p_2}{p_1}\right)^{n-1}$ Finally $\dfrac{T_2}{T_1} = \left(\dfrac{p_2}{p_1}\right)^{(n-1)/n}$ Q.E.D. ◀

Sec. 2.7: Property Relations for Perfect Gases -- *Problems 2.11–2.16*

2.11 *(a) Calculate the density, specific weight, and specific volume of oxygen at 20°C and 50 kN/m² abs. (b) If the oxygen is enclosed in a rigid container of constant volume, what will be the pressure if the temperature is reduced to −100°C?*

SI

(*a*) Table A.5 for oxygen: $R = 260\ \text{m}^2/(\text{s}^2{\cdot}\text{K})$

Eq. 2.5: $\gamma = \dfrac{gp}{RT} = \dfrac{(9.81\ \text{m/s}^2)(50\ \text{kN/m}^2)}{[260\ \text{m}^2/(\text{s}^2{\cdot}\text{K})](273 + 20)\text{K}} = 0.006\,44\ \text{kN/m}^3 = 6.44\ \text{N/m}^3$ ◀

Eq. 2.1: $\rho = \gamma/g = 6.44/9.81 = 0.656\ \text{kg/m}^3$ ◀

Eq. 2.2: $v = 1/\rho = 1/0.656 = 1.524\ \text{m}^3/\text{kg}$ ◀

(*b*) Eq. 2.4: $pv = RT$; $v = \text{const}$, $R = \text{const}$

$\therefore\ \dfrac{p}{T} = \text{constant} = \dfrac{50}{273 + 20} = \dfrac{p_2}{273 - 100}$; $p_2 = 29.5\ \text{kN/m}^2$ ◀

2.12 *(a) If water vapor in the atmosphere has a partial pressure of 0.50 psia and the temperature is 90°F, what is its specific weight? (b) If the barometer reads 14.50 psia, what is the partial pressure of the (dry) air, and what is its specific weight? (c) What is the specific weight of the atmosphere (air plus the water vapor present)?*

BG

(*a*) Table A.5 for water vapor: $R = 2760\ \text{ft}^2/(\text{sec}^2{\cdot}°\text{R})$

Eq. 2.5 for water vapor: $\gamma = \dfrac{32.2(0.50 \times 144)}{2760(460 + 90)} = 0.001\,527\ \text{lb/ft}^3$ ◀

(*b*) $p_{air} = 14.50 - 0.50 = 14.00$ psia ◀

Table A.5 for air: $R = 1715\ \text{ft}^2/(\text{sec}^2{\cdot}°\text{R})$

Eq. 2.5: Air, $\gamma = \dfrac{32.2(14.00 \times 144)}{1715(460 + 90)} = 0.0688\ \text{lb/ft}^3$ ◀

(*c*) Atmos, $\gamma = \gamma_{air} + \gamma_{wvapor} = 0.0688 + 0.001\,527 = 0.0703\ \text{lb/ft}^3$ ◀

2.13 *(a) If water vapor in the atmosphere has a partial pressure of 3500 Pa and the temperature is 30°C, what is its specific weight? (b) If the barometer reads 102 kPa abs, what is the partial pressure of the (dry) air, and what is its specific weight? (c) What is the specific weight of the atmosphere (air plus the water vapor present)?*

SI

(*a*) Table A.5 for water vapor: $R = 462\ \text{m}^2/(\text{s}^2{\cdot}\text{K})$

Eq. 2.5: $\gamma = \dfrac{9.81\ \text{m/s}^2 \times 3500\ \text{N/m}^2}{[462\ \text{m}^2/(\text{s}^2{\cdot}\text{K})](273 + 30)\text{K}} = 0.245\ \text{N/m}^3$ ◀

(*b*) $p_{air} = 102 - (3500/1000) = 98.5$ kPa abs ◀

Table A.5 for air: $R = 287\ \text{m}^2/(\text{s}^2{\cdot}\text{K})$

Eq. 2.5: $\gamma_{air} = \dfrac{gp}{RT} = \dfrac{(9.81\ \text{m/s}^2)(98\,500\ \text{N/m}^2)}{[287\ \text{m}^2/(\text{s}^2{\cdot}\text{K})](273 + 30)\text{K}} = 11.11\ \text{N/m}^3$ ◀

(*c*) $\gamma_{atmos} = \gamma_{air} + \gamma_{wvapor} = 11.11 + 0.245 = 11.36\ \text{N/m}^3$ ◀

2.14 *If the specific weight of water vapor in the atmosphere is 0.0065 lb/ft³ and of the (dry) air is 0.074 lb/ft³ when the temperature is 70°F, (a) what are the partial pressures of the water vapor and the dry air in psia, (b) what is the specific weight of the atmosphere (air and water vapor), and (c) what is the barometric pressure in psia?*

BG

(*a*) Eq. 2.5: $\gamma_{\text{wvapor}} = gp/RT$; Table A.5 for water vapor: $R = 2760$ ft²/(sec²·°R)

$$\therefore\ p = \frac{\gamma RT}{g} = \frac{(0.000\,65\ \text{lb/ft}^3)[2760\ \text{ft}^2/(\text{sec}^2\cdot{}^\circ\text{R})](460 + 70)^\circ\text{R}}{32.2\ \text{ft/sec}^2} = 29.5\ \text{psfa} = 0.205\ \text{psia} \quad \blacktriangleleft$$

Eq. 2.5: $\gamma_{\text{air}} = gp/RT$; Table A.5 for air: $R = 1715$ ft²/(sec²·°R)

$$\therefore\ p = \frac{\gamma RT}{g} = \frac{(0.074\ \text{lb/ft}^3)[1715\ \text{ft}^2/(\text{sec}^2\cdot{}^\circ\text{R})](460 + 70)^\circ\text{R}}{32.2\ \text{ft/sec}^2} = 2090\ \text{psfa} = 14.51\ \text{psia} \quad \blacktriangleleft$$

(*b*) $\gamma_{\text{atmos}} = \gamma_{\text{air}} + \gamma_{\text{wv}} = 0.0740 + 0.000\,65 = 0.747\ \text{lb/ft}^3 \quad \blacktriangleleft$

(*c*) $p_{\text{atm}} = p_{\text{air}} + p_{\text{wv}} = 14.51\ \text{psia} + 0.205\ \text{psia} = 14.72\ \text{psia} \quad \blacktriangleleft$

2.15 *If an artificial atmosphere consists of 20% oxygen and 80% nitrogen by volume, at 101.32 kN/m² abs and 20°C, what are (a) the specific weight and partial pressure of the oxygen, (b) the specific weight and partial pressure of the nitrogen, and (c) the specific weight of the mixture?*

SI

Table A.5: R(oxygen) = 260 m²/(s²·K) ; R(nitrogen) = 297 m²/(s²·K)

Eq. 2.5: 100% O_2: $$\gamma = \frac{(9.81\ \text{m/s}^2)(101.32\ \text{kN/m}^2)}{[260\ \text{m}^2/(\text{s}^2\cdot\text{K})](273 + 20)\text{K}} = 13.05\ \text{N/m}^3$$

100% N_2: $$\gamma = \frac{(9.81\ \text{m/s}^2)(101.32\ \text{kN/m}^2)}{[297\ \text{m}^2/(\text{s}^2\cdot\text{K})](273 + 20)\text{K}} = 11.42\ \text{N/m}^3$$

(*a*) Each m³ of mixture contains 0.2 m³ of O_2 and 0.8 m³ of N_2.

So for 20% O_2: $\gamma = 0.20(13.05) = 2.61\ \text{N/m}^3 \quad \blacktriangleleft$

From Eq. 2.5 for 20% O_2: $$p = \frac{\gamma RT}{g} = \frac{2.61(260)293}{9.81} = 20{,}300\ \text{Pa} = 20.3\ \text{kPa} \quad \blacktriangleleft$$

(*b*) For 80% N_2: $\gamma = 0.80(11.42) = 9.14\ \text{N/m}^3 \quad \blacktriangleleft$

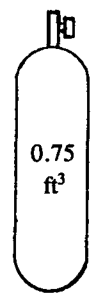
$$p = \frac{\gamma RT}{g} = \frac{9.14(297)293}{9.81} = 81{,}060\ \text{Pa} = 81.1\ \text{kPa} \quad \blacktriangleleft$$

(*c*) Mixture: $\gamma = 2.61 + 9.14 = 11.75\ \text{N/m}^3 \quad \blacktriangleleft$

2.16 *When the ambient air is at 70°F, 14.7 psia, and contains 21% oxygen by volume, 4.5 lb of air are pumped into a scuba tank, capacity 0.75 ft³. (a) What volume of ambient air was compressed? (b) When the filled tank has cooled to ambient conditions, what is the (gage) pressure of the air in the tank? (c) What is the partial pressure (psia) and specific weight of the ambient oxygen? (d) What weight of oxygen was put in the tank? (e) What is the partial pressure (psia) and specific weight of the oxygen in the tank?*

BG

(*a*) From Table A.2: $\gamma_1 = 0.074\,95\ \text{lb/ft}^3$. $\therefore\ \mathcal{V}_{\text{air}} = \dfrac{W}{\gamma_1} = \dfrac{4.5\ \text{lb}}{0.074\,95\ \text{lb/ft}^3} = 60.0\ \text{ft}^3$ ◀



(*b*) $\gamma_2 = \dfrac{W}{\mathcal{V}} = \dfrac{4.5\ \text{lb}}{0.75\ \text{ft}^3} = 6.00\ \text{lb/ft}^3$

From Section 2.7 $n = 1$ for isothermal conditions, so from Eq. 2.6:

$$\frac{p_1}{\rho_1} = \frac{p_2}{\rho_2};\quad \therefore\ p_2 = \left(\frac{\rho_2}{\rho_1}\right)p_1 = \left(\frac{\gamma_2}{\gamma_1}\right)p_1 = \left(\frac{6.00\ \text{lb/ft}^3}{0.074\,95\ \text{lb/ft}^3}\right)14.7\ \text{psia} = 1177\ \text{psia}$$

$p_2 = 1177 - 14.7 = 1162$ psig ◀

(*c*) Table A.5 for oxygen: $R = 1554\ \text{ft}^2/(\text{sec}^2\cdot{}^\circ\text{R})$

Eq. 2.5 for 100% O_2: $\gamma = \dfrac{(32.2\ \text{ft/sec}^2)(14.7\ \text{lb/in}^2)(144\ \text{in}^2/\text{ft}^2)}{[1554\ \text{ft}^2/(\text{sec}^2\cdot{}^\circ\text{R})](460+70)^\circ\text{R}} = 0.0828\ \text{lb/ft}^3$

$\therefore$ for 21% O_2 by volume: $\gamma = 0.21(0.0828) = 0.017\,38\ \text{lb/ft}^3$ ◀

From Eq. 2.5 with 21% O_2: $p = \dfrac{\gamma RT}{g} = \dfrac{(0.017\,38\ \text{lb/ft}^3)[1554\ \text{ft}^2/(\text{sec}^2\cdot{}^\circ\text{R})](530^\circ\text{R})}{32.2\ \text{ft/sec}^2}$

$p = 445$ psfa $= 3.09$ psia ◀

(*d*) $W_{O_2} = \gamma_1 \mathcal{V}_{\text{air}} = (0.017\,38\ \text{lb/ft}^3)60\ \text{ft}^3 = 1.043\ \text{lb}$ ◀

(*e*) $\gamma_2 = \dfrac{W}{\mathcal{V}} = \dfrac{1.043\ \text{lb}}{0.75\ \text{ft}^3} = 1.391\ \text{lb/ft}^3$ ◀

$$p = \frac{\gamma_2 RT}{g} = \frac{1.391(1554)530}{32.2} = 35{,}579\ \text{psfa} = 247\ \text{psia}$$ ◀

Sec. 2.8: Compressibility of Gases -- *Exercises (4)*

2.8.1 *Methane at 22 psia is compressed isothermally, and nitrogen at 16 psia is compressed isentropically. What is the modulus of elasticity of each gas? Which is the more compressible?*

BG

Methane, isothermal: $n = 1$; $E_v = np = (1)22 = 22$ psi ◀

N_2, isentropic: $n = k = 1.40$; $E_v = 1.40(16) = 22.4$ psi ◀

$E_v(\text{methane}) < E_v(N_2)$, methane is more compressible ◀

2.8.2 *Methane at 140 kPa abs is compressed isothermally, and nitrogen at 100 kPa abs is compressed isentropically. What is the modulus of elasticity of each gas? Which is the more compressible?*

SI

Methane, isothermal: $n = 1$; $E_v = np = (1)140 = 140$ kPa ◀

N_2, isentropic: $n = k = 1.40$; $E_v = 1.40(100) = 140$ kPa ◀

$E_v(\text{methane}) = E_v(N_2)$, the compressibilities are equal ◀

2.8.3 *(a) If 10 m^3 of nitrogen at 30°C and 125 kPa are expanded isothermally to 25 m^3, what is the resulting pressure? (b) What would the pressure and temperature have been if the process had been isentropic? The adiabatic exponent k for nitrogen is 1.40.*

SI

(*a*) Isothermal: $p_1 v_1 = p_2 v_2 = \text{constant}$; 125(10/mass) = p_2(25/mass); p_2 = 50 kPa abs ◄

(*b*) Isentropic: $p_1 v_1^{1.40} = p_2 v_2^{1.40}$

$125(10/\text{mass})^{1.40} = p_2(25/\text{mass})^{1.40}$; $p_2 = 125(10/25)^{1.40} = 34.7$ kPa abs ◄

Eq. 2.7: $T_2 = (273+30)(34.7/125)^{0.40/1.40} = 210.0\text{ K} = -63.0°\text{C}$ ◄

2.8.4 *Helium at 25 psia and 65°F is isentropically compressed to one-fifth of its original volume. What is its final pressure?*

BG

Isentropic process: $n = k$; Table A.5 for helium: R = 12,420 ft·lb/(slug·°R), k = 1.66

Eq. 2.4: $v = \dfrac{RT}{p} = \dfrac{12{,}420(460+65)}{25(144)} = 1811\ \text{ft}^3/\text{slug}$

Eq. 2.6: $pv^{1.66} = \text{constant}$; $25(1811)^{1.66} = p_2(1811/5)^{1.66}$; $p_2 = 362$ psia ◄

Sec. 2.8: Compressibility of Gases -- *Problems* 2.17–2.19

2.17 *(a) If 10 ft^3 of carbon dioxide at 50°F and 15 psia is compressed isothermally to 2 ft^3, what is the resulting pressure? (b) What would the pressure and temperature have been if the process had been isentropic? The adiabatic exponent k for carbon dioxide is 1.28.*

BG

(*a*) Isothermal: $n = 1$; Eq. 2.6: $p v$ = constant; 15(10/mass) = p_2(2/mass); p_2 = 75.0 psia ◄

(*b*) Isentropic: $n = k = 1.28$; Eq. 2.6: $pv^n = pv^{1.28}$ = constant; $15(10/\text{mass})^{1.28} = p_2(2/\text{mass})^{1.28}$

$p_2 = 15(10/2)^{1.28} = 117.7$ psia ◄

Eq. 2.7: $T_2 = T_1(p_2/p_1)^{0.28/1.28} = (460 + 50)(117.7/15)^{0.219} = 800°\text{R} = 340°\text{F}$ ◄

2.18 *(a) If 350 L of carbon dioxide at 20°C and 120 kN/m^2 abs is compressed isothermally to 50 L, what is the resulting pressure? (b) What would the pressure and temperature have been if the process had been isentropic? The isentropic exponent k for carbon dioxide is 1.28.*

SI

(*a*) Isothermal, Eq. 2.6: $p v$ = constant; 120(0.35/mass) = p_2(0.05/mass); p_2 = 840 kN/m^2 abs ◄

(*b*) Isentropic: $n = k = 1.28$; Eq. 2.6: $pv^n = pv^{1.28}$ = constant;

$120(0.35/\text{mass})^{1.28} = p_2(0.05/\text{mass})^{1.28}$; $p_2 = 120(0.35/0.05)^{1.28} = 1448$ kN/m^2 abs ◄

Eq. 2.7: $T_2 = (273 + 20)(1448/120)^{0.28/1.28} = 505\text{K} = 232°\text{C}$ ◄

2.19 *Helium at 180 kN/m^2 abs and 20°C is isentropically compressed to one-fifth of its original volume. What is its final pressure?*

SI

Isentropic process: $n = k$; Table A.5 for helium: R = 2077 N·m/(kg·K), k = 1.66

Eq. 2.4: $v = \dfrac{RT}{p} = \dfrac{2077(273+20)}{180(1000)} = 3.38\ \text{m}^3/\text{kg}$

Eq. 2.6: $180(3.38)^{1.66} = p_2(3.38/5)^{1.66}$; $p_2 = 2600$ kPa abs ◄

Sec. 2.11: Viscosity – *Exercises (12)*

2.11.1 *At 60°F what is the kinematic viscosity of the gasoline in Fig. A.2, the specific gravity of which is 0.680? Give the answer in both BG and SI units.*

B

Fig. A.2: 4.8×10^{-6} ft²/sec ◄

Fig. A.2: 4.5×10^{-7} m²/s = 0.0045 cm²/s = 0.45 centistokes ◄

2.11.2 *To what temperature must the fuel oil with the higher specific gravity in Fig. A.2 be heated in order that its kinematic viscosity may be reduced to three times that of water at 40°F?*

BG

Table A.1 for water at 40°F: kinematic viscosity $\nu = 16.64 \times 10^{-6}$ ft²/sec.

Fuel oil: $\nu = 3(16.64 \times 10^{-6}) = 4.99 \times 10^{-5}$ ft²/sec.

Fig. A.2 for fuel oil ($s = 0.968$) with $\nu = 4.99 \times 10^{-5}$ ft²/sec: $T = 375°\text{F}$ ◄

2.11.3 *Compare the ratio of the absolute viscosities of air and water at 70°F with the ratio of their kinematic viscosities at the same temperature and at 14.7 psia.*

BG

Table A.1 for water at 70°F and 14.7 psia: $\mu = 20.50 \times 10^{-6}$ lb·sec/ft², $\nu = 10.59 \times 10^{-6}$ ft²/sec

Table A.2 for air at 70°F and 14.7 psia: $\mu = 0.382 \times 10^{-6}$ lb·sec/ft², $\nu = 0.164 \times 10^{-3}$ ft²/sec

Absolute ratio = μ_{air}/μ_{water} = 0.382/20.50 = 1:53.7 ◄

Kinematic ratio = ν_{air}/ν_{water} = 164/10.59 = 15.5:1 ◄

2.11.4 *A flat plate 200 mm × 750 mm slides on oil (μ = 0.85 N·s/m²) over a large plane surface (Fig. X2.11.4). What force F is required to drag the plate at a velocity v of 1.2 m/s, if the thickness t of the separating oil film is 0.6 mm?*

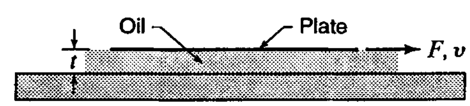


Figure X2.11.4

SI

Eq. 2.9: $\tau = \mu \frac{dv}{dy} = 0.85 \frac{1.2}{0.000\,6} = 1700 \text{ N/m}^2$

From Eq. 2.9: $F = \tau A = 1700(0.20 \times 0.75) = 255$ N ◄

2.11.5 *Refer to Fig. X2.11.4. A flat plate 2 ft × 3 ft slides on oil (μ = 0.024 lb·sec/ft²) over a large plane surface. What force F is required to drag the plate at a velocity v of 4 fps, if the thickness t of the separating oil film is 0.025 in?*

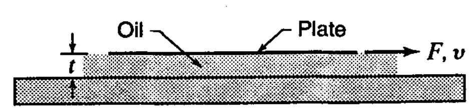


Figure X2.11.4

BG

Eq. 2.9: $\tau = \mu \frac{dV}{dy} = 0.024 \frac{4}{0.025/12} = 46.1 \text{ lb/ft}^2$

From Eq. 2.9: $F = \tau A = (46.1 \text{ lb/ft}^2)(2 \text{ ft} \times 3 \text{ ft}) = 276$ lb ◄

2.11.6 *A liquid has an absolute viscosity of 3.2×10^{-4} lb·sec/ft². It weighs 56 lb/ft³. What are its absolute and kinematic viscosities in SI units?*

B

$$\mu = 3.2 \times 10^{-4} \frac{\text{lb·sec}}{\text{ft}^2}\left(\frac{\text{ft}^2}{144 \text{ in}^2}\right)\frac{6.895 \text{ kN/m}^2}{\text{lb/in}^2} = 15.32 \times 10^{-6} \text{ kN·s/m}^2$$

$$= 15.32 \text{ mN·s/m}^2 = 15.32 \text{ centipoise} \quad ◄$$

Eq. 2.11: $$\nu = \frac{\mu}{\rho} = \frac{15.32 \text{ mN·s/m}^2}{(56/62.4)\text{g/cm}^3} = \frac{15.32 \text{ m(kg·m/s}^2\text{)s/m}^2}{897 \text{ kg/m}^3}$$

$$= 17.07 \times 10^{-6} \text{ m}^2/\text{s} = 0.1707 \text{ stokes} \quad ◄$$

2.11.7 *(a) What is the ratio of the absolute viscosity of water at a temperature of 70°F to that of water at 200°F? (b) What is the ratio of the absolute viscosity of the crude oil in Fig. A.1 (s = 0.925) to that of the gasoline (s = 0.680), both being at a temperature of 60°F? (c) In cooling from 300 to 80°F, what is the ratio of the change of the absolute viscosity of the SAE 30 Western oil to that of the SAE 30 Eastern oil? Refer to Appendix A.*

B

(*a*) Table A.1: $20.50 \times 10^{-6}/(6.37 \times 10^{-6}) = 3.21$ ◄

(*b*) Fig. A.1: $9.0 \times 10^{-2}/(3.1 \times 10^{-4}) = 290$ ◄

(*c*) Fig. A.1: $\dfrac{3.0 \times 10^{-1} - 3.2 \times 10^{-3}}{1.7 \times 10^{-1} - 3.4 \times 10^{-3}} = 1.782$ ◄

Note: Readings from the figure may vary somewhat.

2.11.8 *A space 16 mm wide between two large plane surfaces is filled with SAE 30 Western lubricating oil at 35°C (Fig. X2.11.8). What force F is required to drag a very thin plate of 0.4-m² area between the surfaces at a speed v = 0.25 m/s (a) if this plate is equally spaced between the two surfaces? (b) If t = 5 mm? Refer to Appendix A.*

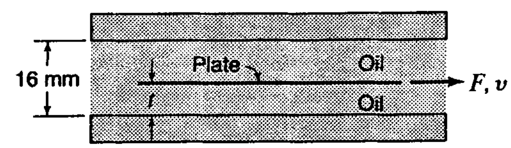


Figure X2.11.8

SI

Fig. A.1 for SAE Western lubricating oil at 35°C:

$\mu = 0.18$ N·s/m²

(*a*) Eq. 2.9: $\tau = 0.18\left(\dfrac{0.25}{8/1000}\right) = 5.63$ N/m² ; From Eq. 2.9: Force $= 5.63(2)0.4 = 4.50$ N ◄

(*b*) Eq. 2.9: $\tau_1 = 0.18\left(\dfrac{0.25}{5/1000}\right) = 9.00$ N/m² ; $\tau_2 = 0.18\left(\dfrac{0.25}{11/1000}\right) = 4.09$ N/m²

From Eq. 2.9: $F_1 = \tau_1 A = 9.00(0.4) = 3.60$ N ; $F_2 = \tau_2 A = 4.09(0.4) = 1.636$ N

$\therefore$ Force $= F_1 + F_2 = 5.24$ N ◄

2.11.9 *A journal bearing consists of an 80-mm shaft in an 80.4-mm sleeve 120 mm long, the clearance space (assumed to be uniform) being filled with SAE 30 Western lubricating oil at 40°C (Fig. X2.11.9). Calculate the rate at which heat is generated at the bearing when the shaft turns at 150 rpm. Express the answer in kN·m/s, J/s, Btu/hr, ft·lb/sec, and hp. Refer to Appendix A.*

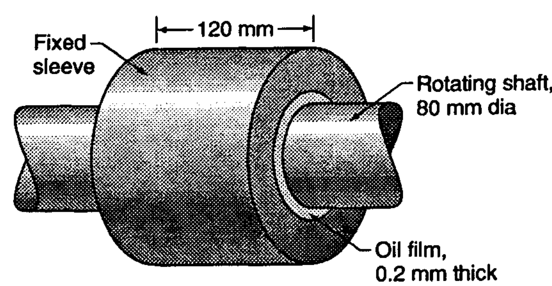


Figure X2.11.9

B

Fig. A.1: $\mu = 1.1 \times 10^{-1} = 0.11$ N·s/m²

Eq. 2.9: $\tau = \mu\dfrac{dv}{dy} = \mu\dfrac{r\omega}{\Delta D/2}$

$= 0.11\dfrac{40(150 \times 2\pi/60)}{0.4/2} = 346$ N/m²

Torque $= (\tau A)r = 346(\pi \times 0.08 \times 0.12)0.04 = 0.417$ N·m

Rate of heat generation $= T\omega = 0.417\left(\dfrac{2\pi \times 150}{60}\right) = 6.55$ N·m/s

$= 6.55$ J/s $= 0.006\ 55$ kN·m/s $= 22.4$ Btu/hr $= 0.008\ 78$ hp $= 4.83$ ft·lb/sec ◄◄

(using conversion factors from inside the back cover).

2.11.10 *In using a rotating-cylinder viscometer, a bottom correction must be applied to account for the drag on the flat bottom of the inner cylinder. Calculate the theoretical amount of this torque correction, neglecting centrifugal effects, for a cylinder of diameter d, rotated at a constant angular velocity ω, in a liquid of absolute viscosity μ, with a clearance Δh between the bottom of the inner cylinder and the floor of the outer one.*

N

Let r = variable radius. $dA = 2\pi r\, dr,\ \tau = \mu r\omega/\Delta h$

Torque $= \int r \times \tau dA = \dfrac{2\pi\mu\omega}{\Delta h}\int_0^{d/2} r^3 dr = \dfrac{\pi\mu\omega}{32\Delta h}d^4$ ◄

2.11.11 *Assuming a velocity distribution as shown in Fig. X2.11.11, which is a parabola having its vertex 12 in from the boundary, calculate the velocity gradients for y = 0, 3, 6, 9, and 12 in. Also calculate the shear stresses in lb/ft² at these points if the fluid's absolute viscosity is 600 cP.*

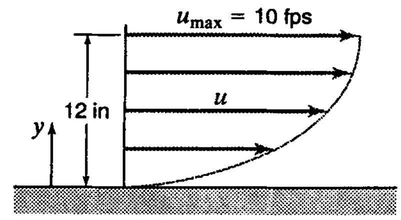


Figure X2.11.11

BG

Back cover: μ = 600 cP = 6 P = 0.6 N·s/m²

μ = 0.6(0.020 885) = 0.012 53 lb·sec/ft². Parabola: $Y = aX^2$

For u in in/sec and y in inches: $120 - u = a(12 - y)^2$

$u = 0$ at $y = 0 \rightarrow a = 120/12^2 = 5/6$; $u = 120 - (5/6)(12 - y)^2$; $du/dy = (5/3)(12 - y)$

Eq. 2.9: $\tau = 0.012\,53\, du/dy$

y (in)	0	3	6	9	12	
du/dy (sec^{-1})	20	15	10	5	0	◄◄
τ (lb/ft²)	0.251	0.1880	0.1253	0.0627	0	◄◄

2.11.12 *Air at 50 psia and 60°F is flowing through a pipe. Table A.2 indicates that its kinetic viscosity ν is 0.158 × 10^{-3} ft²/sec. (a) Why is this ν value incorrect? (b) What is the correct value?*

BG

(*a*) From Sec. 2.11: This ν is incorrect because it varies strongly with pressure (due to ρ changes). ◄

Table A.2 is for p = 14.7 psia, our sample is at p = 50 psia.

(*b*) Sec. 2.11: μ is virtually pressure independent. ∴ $\mu_{50} = \mu_{14.7}$.

Table A.2 for air at 60°F and 14.7 psia: $\mu_{14.7} = 0.374 \times 10^{-6}$ lb·sec/ft², $\rho_{14.7}$ = 0.002 374 slug/ft³

Table A.5 for air: R = 1715 ft²/(sec²·°R).

From Eq. 2.4: $\rho_{50} = \dfrac{p_{50}}{RT} = \dfrac{50 \times 144 \text{ lb/ft}^2}{[1715 \text{ ft}^2/(\text{sec}^2\cdot°\text{R})](460 + 60)°\text{R}} = 0.008\,07$ lb·sec²/ft⁴ (or slug/ft³)

Eq. 2.11: $\nu_{50} = \dfrac{\mu_{50}}{\rho_{50}} = \dfrac{\mu_{14.7}}{\rho_{50}} = \dfrac{0.374 \times 10^{-6} \text{ lb·sec/ft}^2}{0.008\,07 \text{ lb·sec}^2/\text{ft}^4} = 46.3 \times 10^{-6}$ ft²/sec ◄

Sec. 2.11: Viscosity -- *Problems* *2.20–2.28*

2.20 *The absolute viscosity of a certain gas is 0.0234 cP while its kinematic viscosity is 181 cSt, both measured at 1013 mb abs and 100°C. Calculate its approximate molar mass and suggest what gas it may be.*

SI

Eq. 2.11: $\rho = \dfrac{\mu}{\nu} = \dfrac{0.0234 \text{ cP}}{181 \text{ cSt}} = \dfrac{2.34 \times 10^{-5} \text{ N·s/m}^2}{181 \times 10^{-6} \text{ m}^2/\text{s}} = 0.1293$ kg/m³

From Eqs. 2.1 and 2.5: $R = \dfrac{p}{\rho T} = \dfrac{101.3 \text{ kN/m}^3}{(0.1298 \text{ kg/m}^3)(273 + 100)\text{K}} = 2100$ N·m/(kg·K)

Sec. 2.7: $M = R_0/R$ = 8312/2100 = 3.96 ◄ ; Table A.5: The gas may be helium ◄

2.21 *A hydraulic lift of the type commonly used for greasing automobiles consists of a 10.000-in-diameter ram which slides in a 10.006-in-diameter cylinder (Fig. P2.21), the annular space being filled with oil having a kinematic viscosity of 0.0038 ft²/sec and specific gravity of 0.83. If the rate of travel of the ram v is 0.5 fps, find the frictional resistance F when 6 ft of the ram is engaged in the cylinder.*

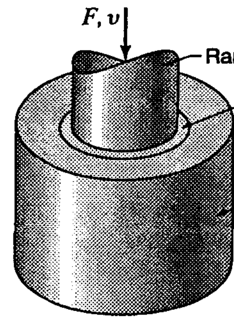


Figure P2.21

BG

$\gamma = 0.83 \times 62.4 = 51.8 \text{ lb/ft}^3, \ \rho = \dfrac{51.8}{32.2} = 1.608 \text{ slug/ft}^3$

Eq. 2.11: $\mu = \nu\rho = 0.0038(1.608) = 0.006\ 11 \text{ lb·sec/ft}^2$

Eq. 2.9: $\tau = \mu \dfrac{dv}{dy} = 0.006\ 11\left(\dfrac{0.5}{0.003/12}\right) = 12.22 \text{ lb/ft}^2$

From Eq. 2.9: Friction force $F = \tau A = 12.22(6 \times \pi \times 10/12) = 192.0$ lb ◄

2.22 *A hydraulic lift of the type commonly used for greasing automobiles consists of a 280.00-mm-diameter ram which slides in a 280.18-mm-diameter cylinder (similar to Fig. P2.21), the annular space being filled with oil having a kinematic viscosity of 0.000 42 m²/s and specific gravity of 0.86. If the rate of travel of the ram is 0.22 m/s, find the frictional resistance when 2 m of the ram is engaged in the cylinder.*

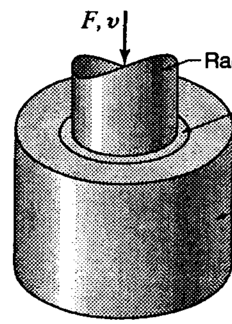


Figure P2.21

SI

$\gamma = 0.86(9810) = 8440 \text{ N/m}^3, \ \rho = 8440/9.81 = 860 \text{ kg/m}^3$

Eq. 2.11: $\mu = \nu\rho = 0.000\ 42(860) = 0.361 \text{ N/m}^2$

Eq. 2.9: $\tau = \mu \dfrac{du}{dy} = 0.361\left(\dfrac{0.22}{0.09/1000}\right) = 883 \text{ N/m}^2$

From Eq. 2.9: Friction force $= \tau A = 883(2\pi 280/1000) = 1553$ N ◄

2.23 *A journal bearing consists of a 8.00-in shaft in a 8.01-in sleeve 10 in long, the clearance space (assumed to be uniform) being filled with SAE 30 Eastern lubricating oil at 100°F. Calculate the rate at which heat is generated at the bearing when the shaft turns at 100 rpm. Refer to Appendix A. Express the answer in Btu/hr.*

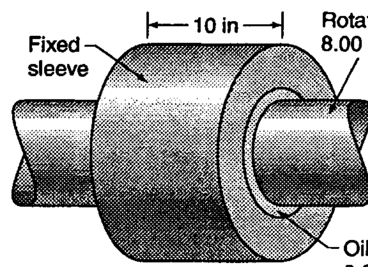


Figure P2.23

BG

Fig. A.1 at 100°F: $\mu = 0.0021 \text{ lb·sec/ft}^2$

$u = \pi\left(\dfrac{8}{12}\right)\left(\dfrac{100}{60}\right) = 3.49 \text{ fps}$

Eq. 2.9: $\tau = (0.0021)\dfrac{3.49}{0.005/12} = 17.59 \text{ lb/ft}^2$

From Eq. 2.9: Friction $= \tau A = 17.59\left(\dfrac{10}{12}\pi\dfrac{8}{12}\right) = 30.7$ lb

Per Sample Prob. 2.9: Energy loss rate $= T\omega = Fu = 30.7(3.49) = 107.2$ ft·lb/sec

Heat generation rate $= \dfrac{107.2 \text{ ft·lb}}{\text{sec}}\left(\dfrac{\text{Btu}}{778 \text{ ft·lb}}\right)\dfrac{3600 \text{ sec}}{\text{hr}} = 496$ Btu/hr ◄

2.24 *Repeat Prob. 2.23 for the case where the sleeve has a diameter of 8.50 in. Compute as accurately as possible the velocity gradient in the fluid at the shaft and sleeve.*

Prob. 2.23: A journal bearing consists of a 8.00-in shaft in a sleeve 10 in long, the clearance space (assumed to be uniform) being filled with SAE 30 Eastern lubricating oil at 100°F. Calculate the rate at which heat is generated at the bearing when the shaft turns at 100 rpm. Refer to Appendix A. Express the answer in Btu/hr.

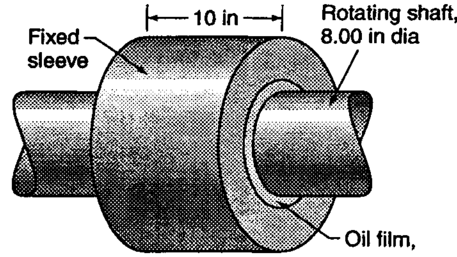


Figure P2.23

BG

Fig. A.1 at 100°F: $\mu = 0.0021$ lb·sec/ft^2

Fig. 2.6*a*: $u_1 = \pi\left(\frac{8.0}{12}\right)\left(\frac{100}{60}\right) = 3.49$ fps

8.00 in = 0.667 ft diameter = 0.333 ft radius ; 8.50 in = 0.708 ft diameter = 0.354 ft radius

$$T = \tau A r = \tau\left(2\pi r\frac{10}{12}\right)r, \quad \text{i.e.,} \quad \tau = \frac{T}{5.24r^2}\ \text{lb/ft}^2$$

$$\text{Eq. 2.9:} \quad \tau = 0.0021\frac{du}{dy} = -0.0021\frac{du}{dr} = \frac{T}{5.24r^2}$$

$$-du = \frac{90.9T}{r^2}dr\ ; \quad -\int_{u_1}^{0} du = 90.9T\int_{0.333}^{0.354} r^{-2}dr = 90.9T\left[\frac{r^{-1}}{-1}\right]_{0.333}^{0.354}$$

$$0 + 3.49 = 90.9T\left(-\frac{1}{0.354} + \frac{1}{0.333}\right) = 90.9T(0.1765); \quad T = \frac{3.49}{16.05} = 0.217\ \text{ft·lb}$$

$$\tau_1 = \frac{0.217}{5.24\times0.333^2} = 0.374\ \text{lb/ft}^2 = 0.0021\left[\frac{du}{dy}\right]_1 ; \quad \left[\frac{du}{dy}\right]_1 = 178.0\ \text{fps/ft} \quad ◀$$

$$\left[\frac{du}{dy}\right]_2 = 178.0\left[\frac{0.333}{0.354}\right]^2 = 157.7\ \text{fps/ft} \quad ◀$$

Rate of energy loss = $T\omega$ = (0.217) 100(2π/60) = 2.28 ft·lb/sec

Rate of heat generation = $2.28\frac{3600}{778}$ = 10.54 Btu/hr ◀

2.25 *A disk spins within an oil-filled enclosure, having 2.4-mm clearance from flat surfaces each side of the disk. The disk surface extends from radius 12 to 86 mm. What torque is required to drive the disk at 660 rpm if the oil's absolute viscosity is 0.12 N·s/m^2?*

SI

Let r = variable radius. $dA = 2\pi r\,dr$, $\tau = \mu r\omega/\Delta h$

$$\text{Torque} = 2\int r \times \tau dA = \frac{4\pi\mu\omega}{\Delta h}\int_{r_1}^{r_2} r^3 dr = \frac{4\pi\mu\omega}{\Delta h}\frac{(r_2^4 - r_1^4)}{4} = \frac{\pi\mu\omega}{\Delta h}(r_2^4 - r_1^4)$$

$$= \frac{\pi \times 0.12\frac{\text{N·s}}{\text{m}^2}\left(660 \times 2\pi\frac{\text{rev/min}}{60\ \text{s/min}}\right)\frac{(86^4 - 12^4)\text{mm}^4}{(10^3\ \text{mm/m})^4}}{\frac{2.4\ \text{mm}}{1000\ \text{mm/m}}} = 0.594\ \text{N·m} \quad ◀$$

2.26 *It is desired to apply the general case of Sample Prob. 2.9 to the extreme cases of a journal bearing ($\alpha = 0$) and an end bearing ($\alpha = 90°$). But when $\alpha = 0$, $r = \tan\alpha = 0$, so $T = 0$; when $\alpha = 90°$, contact area $= \infty$ due to b, so $T = \infty$. Therefore, devise an alternative general derivation which will also provide solutions to these two extreme cases.*

Sample Prob. 2.9: Oil of absolute viscosity μ fills the gap of thickness Y. Obtain an expression for the torque T required to rotate the truncated cone at constant speed ω rad/sec.

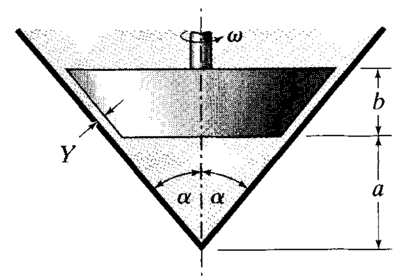
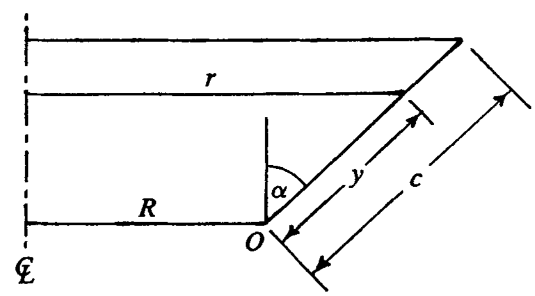


Figure S2.9

N

(*i*) Prevent r from going to zero by prescribing $r_{\min} = R$ (see sketch);

(*ii*) Prevent contact area from becoming infinite by prescribing the sloping dimension c ($=b/\cos\alpha$).



Define y to be the distance along the sloping surface to radius r, with $y = 0$ at point O (and dispense with a and b). Then $\quad r = R + y\sin\alpha$

with (per Fig. S2.9) rotation velocity

$$U = \omega r = \omega(R + y\sin\alpha)$$

Eq. 2.9: $\tau = \mu\dfrac{du}{dy} = \mu\dfrac{U}{Y} = \dfrac{\mu\omega}{Y}(R + y\sin\alpha)$; $dA = 2\pi r\,dy = 2\pi(R + y\sin\alpha)dy$; $dF + \tau dA$

$dT = r\,dF = r\tau dA = (2\pi\mu\omega/Y)(R + y\sin\alpha)^3 dy$; $\qquad T = \int dT = (2\pi\mu\omega/Y)\int_0^c (R + y\sin\alpha)^3 dy$

Expanding and integrating $\quad T = \dfrac{2\pi\mu\omega}{Y}\left(R^3c + \dfrac{3}{2}R^2c^2\sin\alpha + Rc^3\sin^2\alpha + \dfrac{c^4}{4}\sin^3\alpha\right)$ ◄

(*a*) Journal bearing: $\alpha = 0$, $\sin\alpha = 0$, so $\quad T = \dfrac{2\pi\mu\omega}{Y}R^3c$ ◄

(*b*) Flat end bearing: $\alpha = 90°$, $R = 0$, so $\sin\alpha = 1$, let $D = 2c$,

then $\quad T = \dfrac{2\pi\mu\omega}{Y}\dfrac{(D/2)^4}{4} = \dfrac{\pi\mu\omega}{32Y}D^4$ ◄ (This agrees with the solution to Exer. 2.11.10.)

2.27 *Some free air at standard sea-level pressure (101.33 kPa abs) and 20°C has been compressed. Its pressure is now 200 kPa abs and its temperature is 20°C. Table A.2 indicates that its kinetic viscosity ν is 15×10^{-6} m²/s. (a) Why is this ν incorrect? (b) What is the correct value?*

SI

(*a*) From Sec. 2.11: This ν is incorrect because it varies strongly with pressure (due to ρ changes). ◄

Table A.2 is for $p_1 = 101.33$ kPa abs, but we need a value for $p_2 = 200$ kPa abs.

(*b*) Sec. 2.11: μ is virtually independent of pressure. $\therefore\ \mu_2 = \mu_1$.

Table A.2 for air at 20°C and 101.33 kPa abs: $\mu_1 = 18.1 \times 10^{-6}\ \text{N}\cdot\text{s/m}^2$, $\rho_1 = 1.205\ \text{kg/m}^3$.

Table A.5 for air: $R = 287\ \text{m}^2/(\text{s}^2\cdot\text{K})$.

From Eq. 2.4: $\rho_2 = \dfrac{p_2}{RT_2} = \dfrac{200 \times 1000\ \text{N/m}^2}{[287\ \text{m}^2/(\text{s}^2\cdot\text{K})](273 + 20)\text{K}} = 2.38\ \text{N}\cdot\text{s}^2/\text{m}^4$ (or kg/m³)

Eq. 2.11: $\nu_2 = \dfrac{\mu_2}{\rho_2} = \dfrac{\mu_1}{\rho_2} = \dfrac{18.1 \times 10^{-6}\ \text{N}\cdot\text{s/m}^2}{2.38\ \text{N}\cdot\text{s}^2/\text{m}^4} = 7.61 \times 10^{-6}\ \text{m}^2/\text{s}$ ◄

2.28 *Some free air at standard sea-level pressure (101.33 kPa abs) and 20°C has been compressed isentropically. Its pressure is now 194.5 kPa abs and its temperature is 80°C. Table A.2 indicates that its kinetic viscosity ν is 20.9 × 10^{-6} m^2/s. (a) Why is this ν incorrect? (b) What is the correct value? (c) What would the correct value be if the compression were isothermal instead?*

SI

(*a*) From Sec. 2.11: This ν is incorrect because it varies strongly with pressure (due to ρ changes). ◄

Table A.2 is for $p_1 = 101.33$ kPa abs, but we need a value for $p_2 = 194.5$ kPa abs.

(*b*) Table A.2 for air at 20°C and 101.33 kPa abs: $\mu_1 = 18.1 \times 10^{-6}\ \text{N·s/m}^2$, $\rho_1 = 1.205\ \text{kg/m}^3$.

Sec. 2.11: μ is virtually independent of pressure. ∴ at 80°C (Table A.2), $\mu_2 = 20.9 \times 10^{-6}\ \text{N·s/m}^2$

Table A.5 for air: $R = 287\ \text{m}^2/(\text{s}^2\text{·K})$.

From Eq. 2.4: $$\rho_2 = \frac{p_2}{RT_2} = \frac{194.5 \times 1000\ \text{N/m}^2}{[287\ \text{m}^2/(\text{s}^2\text{·K})](273+80)\text{K}} = 1.920\ \text{N·s}^2/\text{m}^4\ (\text{or kg/m}^3)$$

Eq. 2.11: $$\nu_2 = \frac{\mu_2}{\rho_2} = \frac{20.9 \times 10^{-6}\ \text{N·s/m}^2}{1.920\ \text{N·s}^2/\text{m}^4} = 10.89 \times 10^{-6}\ \text{m}^2/\text{s}$$ ◄

(*c*) $T_2 = T_1 = 20$°C. μ is virtually independent of pressure, so $\mu_2 = \mu_1 = 18.1 \times 10^{-6}\ \text{N·s/m}^2$

From Eq. 2.4: $$\rho_2 = \frac{p_2}{RT_2} = \frac{194.5 \times 1000\ \text{N/m}^2}{[287\ \text{m}^2/(\text{s}^2\text{·K})](273+20)\text{K}} = 2.31\ \text{N·s}^2/\text{m}^4\ (\text{or kg/m}^3)$$

Eq. 2.11: $$\nu_2 = \frac{\mu_2}{\rho_2} = \frac{\mu_1}{\rho_2} = \frac{18.1 \times 10^{-6}\ \text{N·s/m}^2}{2.31\ \text{N·s}^2/\text{m}^4} = 7.83 \times 10^{-6}\ \text{m}^2/\text{s}$$ ◄

Sec. 2.12: Surface Tension -- ***Exercises*** *(5)*

2.12.1 *Tap water at 68°F stands in a glass tube of 0.32-in diameter at a height of 4.50 in. What is the true static height?*

BG

Fig. 2.7: Capillary rise ≈ 0.058 in. True static height ≈ 4.50 − 0.058, say 4.44 in ◄

2.12.2 *Distilled water at 20°C stands in a glass tube of 6.0-mm diameter at a height of 18.0 mm. What is the true static height?*

SI

20°C = 68°F; tube dia = 6.0 mm = 0.236 in. Fig. 2.7: Capillary rise ≈ 0.162 in = 4.11 mm

True static height ≈ 18.00 − 4.11 = 13.89 mm ◄

2.12.3 *Use Eq. (2.12) to compute the capillary depression of mercury at 68°F (θ = 140°) to be expected in a 0.05-in-diameter tube.*

BG

Table A.4 for mercury at 68°F: $s = 13.56$, $\sigma = 0.032$ lb/ft.

Eq. 2.12: $$h = \frac{2\sigma\cos 140°}{\gamma r} = \frac{2(0.032)0.766}{13.56 \times 62.4(0.025/12)} = 0.0278\ \text{ft} = 0.334\ \text{in}$$ ◄

2.12.4 *Compute the capillary rise in mm of pure water at 10°C expected in an 0.8-mm-diameter tube.*

SI

Table A.1 at 10°C: $\sigma_{\text{water}} = 0.0742$ N/m, $\gamma = 9.804$ kN/m^3

Eq. 2.12 with $\theta = 0$: $$h = \frac{2\sigma}{\gamma r} = \frac{2(0.0742\ \text{N/m})}{(9804\ \text{N/m}^3)(0.0004\ \text{m})} = 0.0378\ \text{m} = 37.8\ \text{mm}$$ ◄

2.12.5 *Use Eq. (2.12) to compute the capillary rise of water to be expected in an 0.28-in-diameter tube. Assume pure water at 68°F. Compare the result with Fig. 2.7.*

BG

Interpolating from Table A.1 for 68°F: σ = 0.004 99 lb/ft.

Eq. 2.12: $h = \dfrac{2\sigma}{\gamma r} = \dfrac{2(0.004\,99\ \text{lb/ft})(12\ \text{in/ft})}{(62.4\ \text{lb/ft}^3)(0.14/12\ \text{ft})} = 0.1645\ \text{in}$ ◄

Fig. 2.7 shows a capillary rise of ≈ 0.130 in ◄

Sec. 2.12: Surface Tension -- ***Problems*** *2.29–2.32*

2.29 *Pure water at 50°F stands in a glass tube of 0.04 in diameter at a height of 6.78 in. Compute the true static height.*

BG

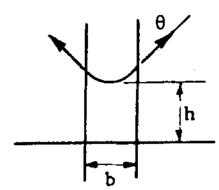
Table A.1 at 50°F: γ = 62.41 lb/ft³, σ = 0.005 09 lb/ft

Eq. 2.12 with $\theta = 0°$: $h = \dfrac{2\sigma}{\gamma r} = \dfrac{2\,(0.005\,09\ \text{lb/ft})}{62.41\ \text{lb/ft}^3\,(0.02/12\ \text{ft})} = 0.0979\ \text{ft} = 1.174\ \text{in}$

True static height = 6.78 in − 1.174 in = 5.61 in ◄

2.30 *(a) Derive an expression for capillary rise (or depression) between two vertical parallel plates. (b) How much would you expect 10°C water to rise (in mm) if the clean glass plates are separated by 1.2 mm?*

SI



(*a*) $(\cos\theta)2\sigma Z = \gamma bhZ$, so $h = 2\sigma\cos\theta/(b\gamma)$ ◄

(*b*) For water, $\theta = 0°$. Table A.1 at 10°C: γ = 9804 N/m³, σ = 0.0742 N/m

$\therefore\ h = \dfrac{2(0.0742\ \text{N/m})\cos 0°}{(1.2/1000\ \text{m})(9804\ \text{N/m}^3)} = 0.012\,61\ \text{m} = 12.61\ \text{mm}$ ◄

2.31 *By how much does the pressure inside a 2-mm-diameter air bubble in 15°C water exceed the pressure in the surrounding water?*

SI

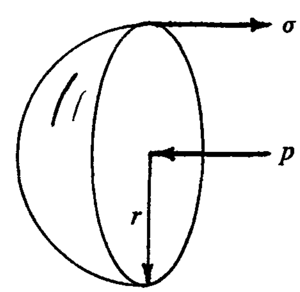


Table A.1 at 15°C: σ = 0.0735 N/m.

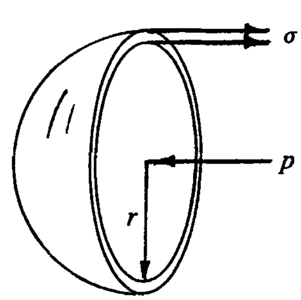
Cut the bubble on a plane through its center, consider force equilibrium.

$\sigma \times$ circumference = $p \times$ area; $\sigma(2\pi r) = p(\pi r^2)$

$p = \dfrac{2\pi r\sigma}{\pi r^2} = \dfrac{2\sigma}{r} = \dfrac{2(0.0735\ \text{N/m})}{0.001\ \text{m}} = 147\ \text{N/m}^2 = 147\ \text{Pa}$ ◄

2.32 *Determine the excess pressure inside an 0.5-in-diameter soap bubble floating in air, given the surface tension of the soap solution is 0.0035 lb/ft.*

SI



Cut the bubble on a plane through its center, and consider force equilibrium, noting that surface tension acts on both the inside and outside surfaces.

$\sigma \times 2 \times$ circumference = $p \times$ area; $2\sigma(2\pi r) = p(\pi r^2)$

$p = \dfrac{4\pi r\sigma}{\pi r^2} = \dfrac{4\sigma}{r} = \dfrac{4(0.0035\ \text{lb/ft})}{0.25/12\ \text{ft}} = 0.672\ \text{lb/ft}^2$

p = 0.004 67 psi ◄

Sec. 2.13: Vapor Pressure of Liquids – *Exercises (2)*

2.13.1 SI *At what pressure in millibars absolute will 70°C water boil?*

Table A.1 at 70°C: p_v = 31.16 kN/m^2 abs. Inside cover: 10 mb = 1 kN/m^2

The water will boil at 31.16 kN/m^2 abs = 311.6 mb abs ◄

2.13.2 BG *At approximately what temperature will water boil in Mexico City (elevation 7400 ft)? Refer to Appendix A.*

Table A.3, by interpolation: p_{at} = 11.21 psia at 7400 ft elevation

Table A.1, by interpolation: p_v water = 11.21 psia at about 198.6°F.

∴ Water boils at 198.6°F ◄

Sec. 2.13: Vapor Pressure of Liquids -- *Problems* 2.33–2.34

2.33 *Water at 170°F in a beaker is placed within an airtight container. Air is gradually pumped out of the container. What reduction below standard atmospheric pressure of 14.7 psia must be achieved before the water boils?*

BG

Table A.1 at 170°F: p_v = 5.99 psia

14.7 − 5.99 = 8.71 psi; the pressure must be reduced by 8.71 psi ◄

2.34 *At approximately what temperature will water boil on top of Mount Kilimanjaro (elevation 5895 m)? Refer to Appendix A.*

SI

Table A.3, by interpolation: p_{at} = 47.934 kPa abs at 5895 m elevation.

Table A.1, by interpolation: p_v of water = 47.934 kPa abs at about 80.26°C.

So water will boil there at about 80.3°C ◄