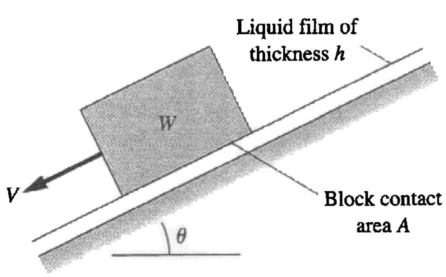
P1.43 According to rarefied gas theory [18], the no-slip condition begins to fail in tube flow when the mean free path of the gas is as large as 0.005 times the tube diameter. Consider helium at 20°C (Table A.4) flowing in a tube of diameter 1 cm. Using the theory of Prob. P1.5 (which is "correct", not "proposed"), find the helium pressure for which this no-slip failure begins.

P1.44 The values for SAE 30 oil in Table 1.4 are strictly "representative," not exact, because lubricating oils vary considerably according to the type of crude oil from which they are refined. The Society of Automotive Engineers [26] allows certain kinematic viscosity *ranges* for all lubricating oils: for SAE 30, $9.3 < \nu < 12.5$ mm²/s at 100°C. SAE 30 oil density can also vary ±2 percent from the tabulated value of 891 kg/m³. Consider the following data for an acceptable grade of SAE 30 oil:

T, °C	0	20	40	60	80	100
μ, kg/(m·s)	2.00	0.40	0.11	0.042	0.017	0.0095

How does this oil compare with the plot in Appendix Fig. A.1? How well does the data fit Andrade's equation in Prob. 1.40?

P1.45 A block of weight W slides down an inclined plane while lubricated by a thin film of oil, as in Fig. P1.45. The film contact area is A and its thickness is h. Assuming a linear velocity distribution in the film, derive an expression for the "terminal" (zero-acceleration) velocity V of the block. Find the terminal velocity of the block if the block mass is 6 kg, $A = 35$ cm², $\theta = 15°$, and the film is 1-mm-thick SAE 30 oil at 20°C.



P1.45

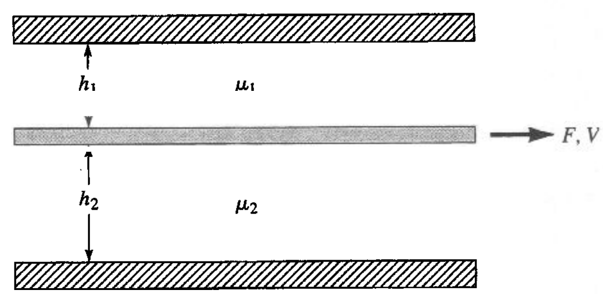
P1.46 A simple and popular model for two nonnewtonian fluids in Fig. 1.9*a* is the *power-law*:

$$\tau \approx C\left(\frac{du}{dy}\right)^n$$

where C and n are constants fit to the fluid [16]. From Fig. 1.9*a*, deduce the values of the exponent n for which the fluid is (*a*) newtonian, (*b*) dilatant, and (*c*) pseudoplastic. Consider the specific model constant $C = 0.4$ N · sⁿ/m², with the fluid being sheared between two parallel plates as in Fig. 1.8. If the shear stress in the fluid is 1200 Pa, find the velocity V of the upper plate for the cases (*d*) $n = 1.0$, (*e*) $n = 1.2$, and (*f*) $n = 0.8$.

P1.47 A shaft 6.00 cm in diameter is being pushed axially through a bearing sleeve 6.02 cm in diameter and 40 cm long. The clearance, assumed uniform, is filled with oil whose properties are $\nu = 0.003$ m²/s and SG= 0.88. Estimate the force required to pull the shaft at a steady velocity of 0.4 m/s.

P1.48 A thin plate is separated from two fixed plates by very viscous liquids μ_1 and μ_2, respectively, as in Fig. P1.48. The plate spacings h_1 and h_2 are unequal, as shown. The contact area is A between the center plate and each fluid. (*a*) Assuming a linear velocity distribution in each fluid, derive the force F required to pull the plate at velocity V. (*b*) Is there a necessary *relation* between the two viscosities, μ_1 and μ_2?



P1.48

P1.49 An amazing number of commercial and laboratory devices have been developed to measure fluid viscosity, as described in Refs. 29 and 49. Consider a concentric shaft, as in Prob. 1.47, but now fixed axially and rotated inside the sleeve. Let the inner and outer cylinders have radii r_i and r_o, respectively, with total sleeve length L. Let the rotational rate be Ω (rad/s) and the applied torque be M. Using these parameters, derive a theoretical relation for the viscosity μ of the fluid between the cylinders.

P1.50 A simple viscometer measures the time t for a solid sphere to fall a distance L through a test fluid of density ρ. The fluid viscosity μ is then given by

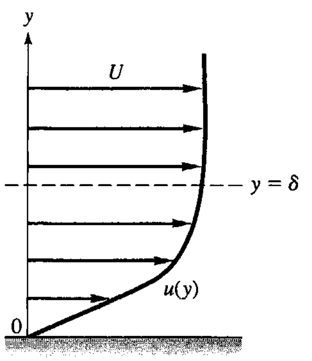
$$\mu \approx \frac{W_{net}t}{3\pi DL} \quad \text{if} \quad t \geq \frac{2\rho DL}{\mu}$$

where D is the sphere diameter and W_{net} is the sphere net weight in the fluid. (*a*) Prove that both of these formulas are dimensionally homogeneous. (*b*) Suppose that a 2.5 mm diameter aluminum sphere (density 2700 kg/m^3) falls in an oil of density 875 kg/m^3. If the time to fall 50 cm is 32 s, estimate the oil viscosity and verify that the inequality is valid.

P1.51 An approximation for the boundary-layer shape in Figs. 1.6*b* and P1.51 is the formula

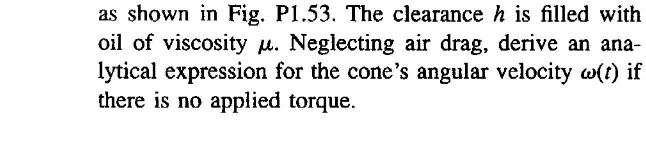
$$u(y) \approx U \sin\left(\frac{\pi y}{2\delta}\right), \qquad 0 \le y \le \delta$$

where U is the stream velocity far from the wall and δ is the boundary layer thickness, as in Fig. P.151. If the fluid is helium at 20°C and 1 atm, and if $U = 10.8$ m/s and $\delta = 3$ cm, use the formula to (*a*) estimate the wall shear stress τ_w in Pa, and (*b*) find the position in the boundary layer where τ is one-half of τ_w.



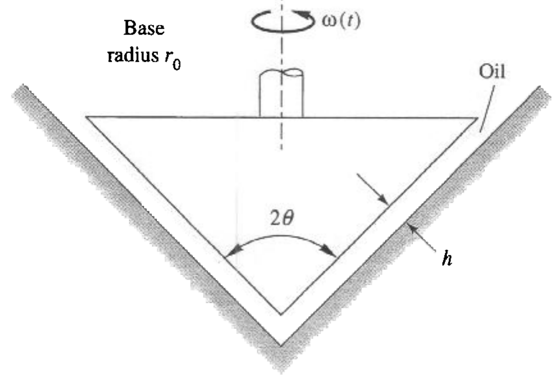
P1.51

P1.52 The belt in Fig. P1.52 moves at a steady velocity V and skims the top of a tank of oil of viscosity μ, as shown. Assuming a linear velocity profile in the oil, develop a simple formula for the required belt-drive power P as a function of (h, L, V, b, μ). What belt-drive power P, in watts, is required if the belt moves at 2.5 m/s over SAE 30W oil at 20°C, with $L = 2$ m, $b = 60$ cm, and $h = 3$ cm?



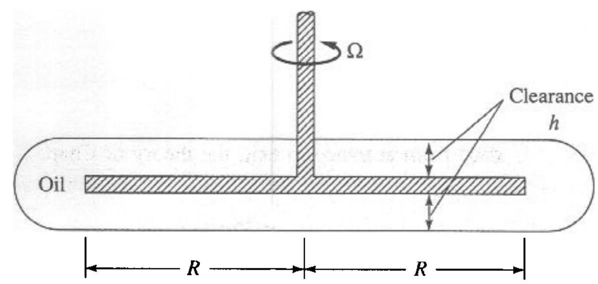
P1.52

***P1.53** A solid cone of angle 2θ, base r_0, and density ρ_c is rotating with initial angular velocity ω_0 inside a conical seat, as shown in Fig. P1.53. The clearance h is filled with oil of viscosity μ. Neglecting air drag, derive an analytical expression for the cone's angular velocity $\omega(t)$ if there is no applied torque.



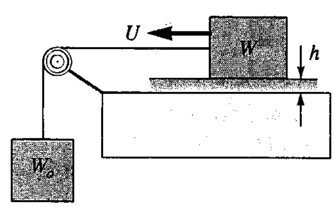
P1.53

***P1.54** A disk of radius R rotates at an angular velocity Ω inside a disk-shaped container filled with oil of viscosity μ, as shown in Fig. P1.54. Assuming a linear velocity profile and neglecting shear stress on the outer disk edges, derive a formula for the viscous torque on the disk.



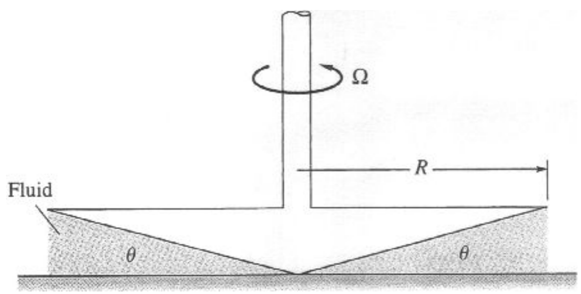
P1.54

P1.55 A block of weight W is being pulled over a table by another weight W_o, as shown in Fig. P1.55. Find an algebraic formula for the steady velocity U of the block if it slides on an oil film of thickness h and viscosity μ. The block bottom area A is in contact with the oil. Neglect the cord weight and the pulley friction. Assume a linear velocity profile in the oil film.



P1.55

***P1.56** The device in Fig. P1.56 is called a *cone-plate viscometer* [29]. The angle of the cone is very small, so that sin $\theta \approx \theta$, and the gap is filled with the test liquid. The torque M to rotate the cone at a rate Ω is measured. Assuming a linear velocity profile in the fluid film, derive an expression for fluid viscosity μ as a function of (M, R, Ω, θ).



P1.56

P1.57 For the geometry of Prob. P1.55, (a) solve the *unsteady* problem $U(t)$ where the block starts from rest and accelerates toward the final steady velocity U_o of Prob. P1.55. (*b*) As a separate issue, if the table were instead *sloped* at an angle θ toward the pulley, state the criterion for whether the block moves up or down the table.

***P1.58** The laminar pipe flow example of Prob. 1.12 can be used to design a *capillary viscometer* [29]. If Q is the volume flow rate, L is the pipe length, and Δp is the pressure drop from entrance to exit, the theory of Chap. 6 yields a formula for viscosity:

$$\mu = \frac{\pi r_0^4 \Delta p}{8LQ}$$

Pipe end effects are neglected [29]. Suppose our capillary has $r_0 = 2$ mm and $L = 25$ cm. The following flow rate and pressure drop data are obtained for a certain fluid:

Q, m³/h	0.36	0.72	1.08	1.44	1.80
Δp, kPa	159	318	477	1274	1851

What is the viscosity of the fluid? *Note:* Only the first three points give the proper viscosity. What is peculiar about the last two points, which were measured accurately?

P1.59 A solid cylinder of diameter D, length L, and density ρ_s falls due to gravity inside a tube of diameter D_0. The clearance, $D_0 - D << D$, is filled with fluid of density ρ and viscosity μ. Neglect the air above and below the cylinder. Derive a formula for the terminal fall velocity of the cylinder. Apply your formula to the case of a steel cylinder, $D = 2$ cm, $D_0 = 2.04$ cm, $L = 15$ cm, with a film of SAE 30 oil at 20°C.

P1.60 Pipelines are cleaned by pushing through them a close-fitting cylinder called a *pig*. The name comes from the squealing noise it makes sliding along. Reference 50 describes a new nontoxic pig, driven by compressed air, for cleaning cosmetic and beverage pipes. Suppose the pig diameter is 5-15/16 in and its length 26 in. It cleans a 6-in-diameter pipe at a speed of 1.2 m/s. If the clearance is filled with glycerin at 20°C, what pressure difference, in pascals, is needed to drive the pig? Assume a linear velocity profile in the oil and neglect air drag.

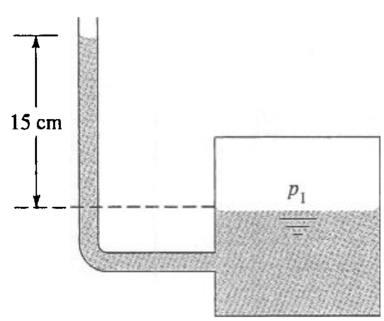
***P1.61** An air-hockey puck has a mass of 50 g and is 9 cm in diameter. When placed on the air table, a 20°C air film, of 0.12-mm thickness, forms under the puck. The puck is struck with an initial velocity of 10 m/s. Assuming a linear velocity distribution in the air film, how long will it take the puck to (*a*) slow down to 1 m/s and (*b*) stop completely? Also, (*c*) how far along this extremely long table will the puck have traveled for condition (*a*)?

P1.62 The hydrogen bubbles that produced the velocity profiles in Fig. 1.15 are quite small, $D \approx 0.01$ mm. If the hydrogen–water interface is comparable to air–water and the water temperature is 30°C, estimate the excess pressure within the bubble.

P1.63 Derive Eq. (1.34) by making a force balance on the fluid interface in Fig. 1.11*c*.

P1.64 A shower head emits a cylindrical jet of clean 20°C water into air. The pressure inside the jet is approximately 200 Pa greater than the air pressure. Estimate the diameter of the jet in mm.

P1.65 The system in Fig. P1.65 is used to calculate the pressure p_1 in the tank by measuring the 15-cm height of liquid in the 1-mm-diameter tube. The fluid is at 60°C. Calculate the true fluid height in the tube and the percentage error due to capillarity if the fluid is (*a*) water or (*b*) mercury.

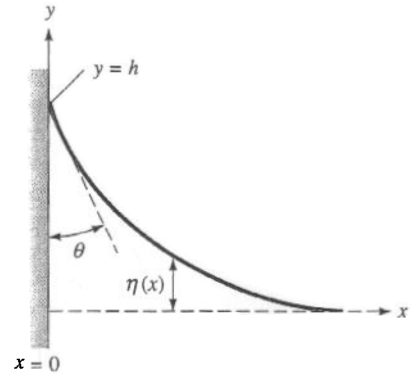


P1.65

P1.66 A thin wire ring, 3 cm in diameter, is lifted from a water surface at 20°C. Neglecting the wire weight, what is the force required to lift the ring? Is this a good way to measure surface tension? Should the wire be made of any particular material?

P1.67 A vertical concentric annulus, with outer radius r_o and inner radius r_i, is lowered into a fluid of surface tension Y and contact angle $\theta < 90°$. Derive an expression for the capillary rise h in the annular gap if the gap is very narrow.

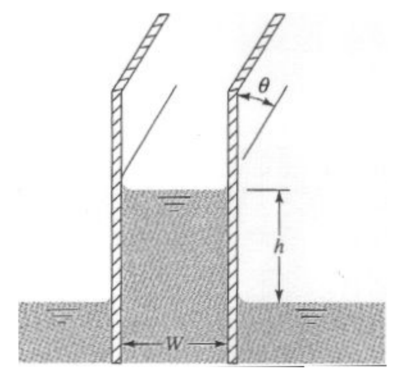
***P1.68** Make an analysis of the shape $\eta(x)$ of the water–air interface near a plane wall, as in Fig. P1.68, assuming that the slope is small, $R^{-1} \approx d^2\eta/dx^2$. Also assume that the pressure difference across the interface is balanced by the specific weight and the interface height, $\Delta p \approx \rho g \eta$. The boundary conditions are a wetting contact angle θ at $x = 0$ and a horizontal surface $\eta = 0$ as $x \to \infty$. What is the maximum height h at the wall?



P1.68

P1.69 A solid cylindrical needle of diameter d, length L, and density ρ_n may float in liquid of surface tension Y. Neglect buoyancy and assume a contact angle of 0°. Derive a formula for the maximum diameter d_{max} able to float in the liquid. Calculate d_{max} for a steel needle (SG = 7.84) in water at 20°C.

P1.70 Derive an expression for the capillary height change h for a fluid of surface tension Y and contact angle θ between two vertical parallel plates a distance W apart, as in Fig. P1.70. What will h be for water at 20°C if $W = 0.5$ mm?



P1.70

***P1.71** A soap bubble of diameter D_1 coalesces with another bubble of diameter D_2 to form a single bubble D_3 with the same amount of air. Assuming an isothermal process, derive an expression for finding D_3 as a function of D_1, D_2, p_{atm}, and Y.

P1.72 Early mountaineers boiled water to estimate their altitude. If they reach the top and find that water boils at 84°C, approximately how high is the mountain?

P1.73 A small submersible moves at velocity V, in fresh water at 20°C, at a 2-m depth, where ambient pressure is 131 kPa. Its critical cavitation number is known to be $C_a = 0.25$. At what velocity will cavitation bubbles begin to form on the body? Will the body cavitate if $V = 30$ m/s and the water is cold (5°C)?

P1.74 Oil, with a vapor pressure of 20 kPa, is delivered through a pipeline by equally spaced pumps, each of which increases the oil pressure by 1.3 MPa. Friction losses in the pipe are 150 Pa per meter of pipe. What is the maximum possible pump spacing to avoid cavitation of the oil?

P1.75 An airplane flies at 555 mi/h. At what altitude in the standard atmosphere will the airplane's Mach number be exactly 0.8?

P1.76 Estimate the speed of sound of steam at 200°C and 400 kPa (*a*) by an ideal-gas approximation (Table A.4) and (*b*) using EES (or the steam tables) and making small isentropic changes in pressure and density and approximating Eq. (1.38).

***P1.77** The density of 20°C gasoline varies with pressure approximately as follows:

p, atm	1	500	1000	1500
ρ, lbm/ft^3	42.45	44.85	46.60	47.98

Use these data to estimate (*a*) the speed of sound (m/s) and (*b*) the bulk modulus (MPa) of gasoline at 1 atm.

P1.78 Sir Isaac Newton measured the speed of sound by timing the difference between seeing a cannon's puff of smoke and hearing its boom. If the cannon is on a mountain 5.2 mi away, estimate the air temperature in degrees Celsius if the time difference is (*a*) 24.2 s and (*b*) 25.1 s.

P1.79 Even a tiny amount of dissolved gas can drastically change the speed of sound of a gas–liquid mixture. By estimating the pressure–volume change of the mixture, Olson [51] gives the following approximate formula:

$$a_{mixture} \approx \sqrt{\frac{p_g K_l}{[x\rho_g + (1-x)\rho_l][xK_l + (1-x)p_g]}}$$

Where x is the volume fraction of gas, K is the bulk modulus, and subscripts l and g denote the liquid and gas,