EXAMPLE 1.10

Given the steady two-dimensional velocity distribution

$$u = Kx \qquad v = -Ky \qquad w = 0 \tag{1}$$

where K is a positive constant, compute and plot the streamlines of the flow, including directions, and give some possible interpretations of the pattern.

Solution

Since time does not appear explicitly in Eq. (1), the motion is steady, so that streamlines, pathlines, and streaklines will coincide. Since $w = 0$ everywhere, the motion is two dimensional, in the xy plane. The streamlines can be computed by substituting the expressions for u and v into Eq. (1.41):

$$\frac{dx}{Kx} = -\frac{dy}{Ky}$$

or

$$\int \frac{dx}{x} = -\int \frac{dy}{y}$$

Integrating, we obtain $\ln x = -\ln y + \ln C$, or

$$xy = C \qquad \textit{Ans.} \ (2)$$

This is the general expression for the streamlines, which are hyperbolas. The complete pattern is plotted in Fig. E1.10 by assigning various values to the constant C. The arrowheads can be determined only by returning to Eqs. (1) to ascertain the velocity component directions, assuming K is positive. For example, in the upper right quadrant ($x > 0$, $y > 0$), u is positive and v is negative; hence the flow moves down and to the right, establishing the arrowheads as shown.

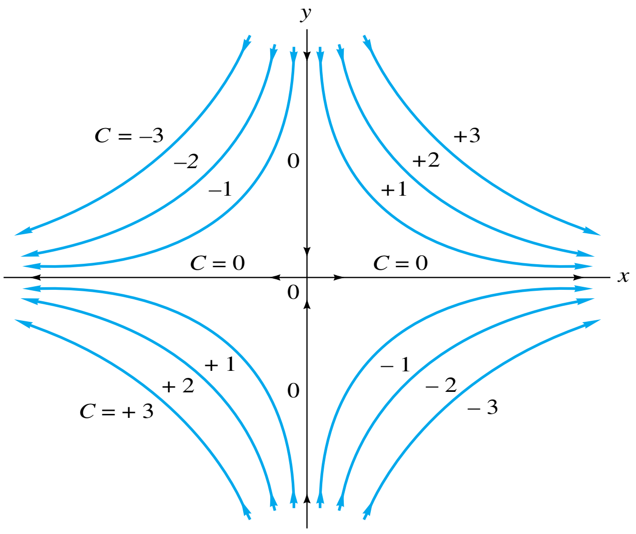


Fig. E1.10 Streamlines for the velocity distribution given by Eq. (1), for $K > 0$.

Note that the streamline pattern is entirely independent of constant K. It could represent the impingement of two opposing streams, or the upper half could simulate the flow of a single downward stream against a flat wall. Taken in isolation, the upper right quadrant is similar to the flow in a 90° corner. This is definitely a realistic flow pattern and is discussed again in Chap. 8.

Finally note the peculiarity that the two streamlines ($C = 0$) have opposite directions and intersect. This is possible only at a point where $u = v = w = 0$, which occurs at the origin in this case. Such a point of zero velocity is called a *stagnation point*.

A streakline can be produced experimentally by the continuous release of marked particles (dye, smoke, or bubbles) from a given point. Figure 1.17 shows two examples. The flow in Fig. 1.17*b* is unsteady and periodic due to the flapping of the plate against the oncoming stream. We see that the dash-dot streakline does not coincide with either the streamline or the pathline passing through the same release point. This is characteristic of unsteady flow, but in Fig. 1.17*a* the smoke filaments form streaklines which are identical to the streamlines and pathlines. We noted earlier that this coincidence of lines is always true of steady flow: Since the velocity never changes magnitude or direction at any point, every particle which comes along repeats the behavior of its earlier neighbors.

Methods of experimental flow visualization include the following:

1. Dye, smoke, or bubble discharges
2. Surface powder or flakes on liquid flows
3. Floating or neutral-density particles
4. Optical techniques which detect density changes in gas flows: shadowgraph, schlieren, and interferometer
5. Tufts of yarn attached to boundary surfaces
6. Evaporative coatings on boundary surfaces
7. Luminescent fluids or additives

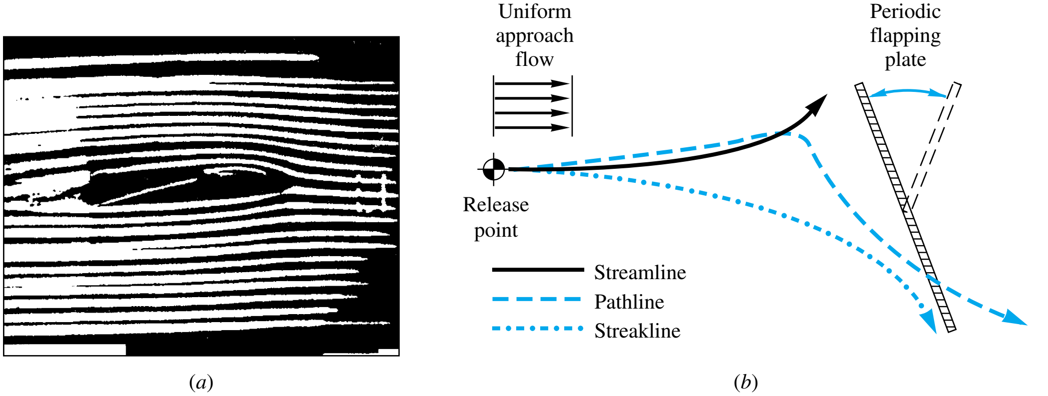


Fig. 1.17 Experimental visualization of steady and unsteady flow: (*a*) steady flow past an airfoil visualized by smoke filaments *(C. A. A. SCIENTIFIC—Prime Movers Laboratory Systems);* (*b*) unsteady flow past an oscillating plate with a point bubble release (from an experiment in Ref. 17).

The mathematical implications of flow-pattern analysis are discussed in detail in Ref. 18. References 19 and 20 are beautiful albums of photographs. References 21 and 22 are monographs on flow visualization.

1.10 The Engineering Equation Solver

Most of the examples and exercises in this text are amenable to direct calculation without guessing or iteration or looping. Until recently, only such direct problem assignments, whether "plug-and-chug" or more subtle, were appropriate for undergraduate engineering courses. However, the recent introduction of computer software *solvers* makes almost any set of algebraic relations viable for analysis and solution. The solver recommended here is the *Engineering Equation Solver* (EES) developed by Klein and Beckman [33] and described in Appendix E.

Any software solver should handle a purely mathematical set of relations, such as the one posed in Ref. 33: $X \ln (X) = Y^3$, $X^{1/2} = 1/Y$. Submit that pair to any commercial solver and you will no doubt receive the answer: $X = 1.467$, $Y = 0.826$. However, for engineers, in the author's opinion, EES is superior to most solvers because (1) equations can be entered in any order; (2) scores of mathematical formulas are built-in, such as the Bessel functions; and (3) thermophysical properties of many fluids are built-in, such as the steam tables [13]. Both metric and English units are allowed. Equations need not be written in the traditional BASIC or FORTRAN style. For example, $X - Y + 1 = 0$ is perfectly satisfactory; there is no need to retype this as $X = Y - 1$.

For example, reconsider Example 1.7 as an EES exercise. One would first enter the reference properties p_0 and ρ_0 plus the curve-fit constants B and n:

```
Pz = 1.0
Rhoz = 2.0
B = 3000
n = 7
```

Then specify the given pressure ratio and the curve-fit relation, Eq. (1.19), for the equation of state of water:

```
P = 1100*Pz
P/Pz = (B + 1)*(Rho/Rhoz)^n - B
```

If you request an initial opinion from the CHECK/FORMAT menu, EES states that there are six equations in six unknowns and there are no obvious difficulties. Then request SOLVE from the menu and EES quickly prints out Rho = 2.091, the correct answer as seen already in Ex. 1.7. It also prints out values of the other five variables. Occasionally EES reports "unable to converge" and states what went wrong (division by zero, square root of a negative number, etc.). One needs only to improve the guesses and ranges of the unknowns in Variable Information to assist EES to the solution.

In subsequent chapters we will illustrate some implicit (iterative) examples by using EES and will also assign some advanced problem exercises for which EES is an ideal approach. The use of an engineering solver, notably EES, is recommended to all engineers in this era of the personal computer.

1.11 Uncertainty of Experimental Data

Earlier in this chapter we referred to the *uncertainty* of the principle of corresponding states in discussing Fig. 1.5. Uncertainty is a fact of life in engineering. We rarely know any engineering properties or variables to an extreme degree of accuracy. Therefore, we need to know the *uncertainty* U of our data, usually defined as the band within which the experimenter is 95 percent confident that the true value lies (Refs. 30, 31). In Fig. 1.5, we were given that the uncertainty of μ/μ_c is $U \approx \pm 20$ percent.

Fluid mechanics is heavily dependent upon experimentation, and the data uncertainty is needed before we can use it for prediction or design purposes. Sometimes uncertainty completely changes our viewpoint. As an offbeat example, suppose that astronomers reported that the length of the earth year was 365.25 days "give or take a couple of months." First, that would make the five-figure accuracy ridiculous, and the year would better be stated as $Y \approx 365 \pm 60$ days. Second, we could no longer plan confidently or put together accurate calendars. Scheduling Christmas vacation would be chancy.

Multiple variables make uncertainty estimates cumulative. Suppose a given result P depends upon N variables, $P = P(x_1, x_2, x_3, \ldots, x_N)$, each with its own uncertainty; for example, x_1 has uncertainty δx_1. Then, by common agreement among experimenters, the total uncertainty of P is calculated as a root-mean-square average of all effects:

$$\delta P = \left[\left(\frac{\partial P}{\partial x_1}\delta x_1\right)^2 + \left(\frac{\partial P}{\partial x_2}\delta x_2\right)^2 + \cdots + \left(\frac{\partial P}{\partial x_N}\delta x_N\right)^2\right]^{1/2} \tag{1.43}$$

This calculation is statistically much more probable than simply adding linearly the various uncertainties δx_i, thereby making the unlikely assumption that all variables simultaneously attain maximum error. Note that it is the responsibility of the experimenter to establish and report accurate estimates of all the relevant uncertainties δx_i.

If the quantity P is a simple power-law expression of the other variables, for example, $P = \text{Const}\ x_1^{n_1} x_2^{n_2} x_3^{n_3} \ldots$, then each derivative in Eq. (1.43) is proportional to P and the relevant power-law exponent and is inversely proportional to that variable.

If $P = \text{Const}\ x_1^{n_1} x_2^{n_2} x_3^{n_3} \ldots$, then

$$\frac{\partial P}{\partial x_1} = \frac{n_1 P}{x_1}, \quad \frac{\partial P}{\partial x_2} = \frac{n_2 P}{x_2}, \quad \frac{\partial P}{\partial x_3} = \frac{n_3 P}{x_3}, \quad \cdots$$

Thus, from Eq. (1.43),

$$\frac{\delta P}{P} = \left[\left(n_1 \frac{\delta x_1}{x_1}\right)^2 + \left(n_2 \frac{\delta x_2}{x_2}\right)^2 + \left(n_3 \frac{\delta x_3}{x_3}\right)^2 + \cdots\right]^{1/2} \tag{1.44}$$

Evaluation of δP is then a straightforward procedure, as in the following example.

EXAMPLE 1.11

The so-called dimensionless Moody pipe-friction factor f, plotted in Fig. 6.13, is calculated in experiments from the following formula involving pipe diameter D, pressure drop Δp, density ρ, volume flow rate Q, and pipe length L:

$$f = \frac{\pi^2}{32} \frac{D^5 \Delta p}{\rho Q^2 L}$$

Measurement uncertainties are given for a certain experiment: for D: 0.5 percent, Δp: 2.0 percent, ρ: 1.0 percent, Q: 3.5 percent, and L: 0.4 percent. Estimate the overall uncertainty of the friction factor f.

Solution

The coefficient $\pi^2/32$ is assumed to be a pure theoretical number, with no uncertainty. The other variables may be collected using Eqs. (1.43) and (1.44):

$$U = \frac{\delta f}{f} = \left[\left(5\frac{\delta D}{D}\right)^2 + \left(1\frac{\delta \Delta p}{\Delta p}\right)^2 + \left(1\frac{\delta \rho}{\rho}\right)^2 + \left(2\frac{\delta Q}{Q}\right)^2 + \left(1\frac{\delta L}{L}\right)^2\right]^{1/2}$$

$$= [\{5(0.5\%)\}^2 + (2.0\%)^2 + (1.0\%)^2 + \{2(3.5\%)\}^2 + (0.4\%)^2]^{1/2} \approx 7.8\% \qquad \textit{Ans.}$$

By far the dominant effect in this particular calculation is the 3.5 percent error in Q, which is amplified by doubling, due to the power of 2 on flow rate. The diameter uncertainty, which is quintupled, would have contributed more had δD been larger than 0.5 percent.

1.12 The Fundamentals of Engineering (FE) Examination

The road toward a professional engineer's license has a first stop, the Fundamentals of Engineering Examination, known as the FE exam. It was formerly known as the Engineer-in-Training (E-I-T) Examination. This 8-h national test will probably soon be required of all engineering graduates, not just for licensure, but as a student-assessment tool. The 120-problem morning session covers many general studies:

Chemistry	Computers	Dynamics
Electric circuits	Engineering economics	***Fluid Mechanics***
Materials science	Mathematics	Mechanics of materials
Statics	Thermodynamics	Ethics

For the 60-problem afternoon session you may choose chemical, civil, electrical, industrial, or mechanical engineering or take more general-engineering problems for remaining disciplines. As you can see, *fluid mechanics* is central to the FE exam. Therefore, this text includes a number of end-of-chapter FE problems where appropriate.

The format for the FE exam questions is multiple-choice, usually with five selections, chosen carefully to tempt you with plausible answers if you used incorrect units or forgot to double or halve something or are missing a factor of π, etc. In some cases, the selections are unintentionally ambiguous, such as the following example from a previous exam:

Transition from laminar to turbulent flow occurs at a Reynolds number of
(A) 900 (B) 1200 (C) 1500 (D) 2100 (E) 3000

The "correct" answer was graded as (D), Re = 2100. Clearly the examiner was thinking, but forgot to specify, Re_d for *flow in a smooth circular pipe,* since (see Chaps. 6 and 7) transition is highly dependent upon geometry, surface roughness, and the length scale used in the definition of Re. The moral is not to get peevish about the exam but simply to go with the flow (pun intended) and decide which answer best fits an undergraduate-training situation. Every effort has been made to keep the FE exam questions in this text unambiguous.

1.13 Problem-Solving Techniques

Fluid flow analysis generates a plethora of problems, 1500 in this text alone! To solve these problems, one must deal with various equations, data, tables, assumptions, unit systems, and numbers. The writer recommends these problem-solving steps:

1. Gather all the given system parameters and data in one place.
2. Find, from tables or charts, all needed fluid property data: ρ, μ, c_p, k, Υ, etc.
3. Use SI units (N, s, kg, m) if possible, and no conversion factors will be necessary.
4. Make sure what is *asked*. It is all too common for students to answer the wrong question, for example, reporting mass flow instead of volume flow, pressure instead of pressure gradient, drag force instead of lift force. Engineers are expected to read carefully.
5. Make a detailed sketch of the system, with everything clearly labeled.
6. Think carefully and then list your *assumptions*. Here knowledge is power; you should not guess the answer. You must be able to decide correctly if the flow can be considered steady or unsteady, compressible or incompressible, one-dimensional, or multidimensional, viscous or inviscid, and whether a control volume or partial differential equations are needed.
7. Based on steps 1 to 6 above, write out the appropriate equations, data correlations, and fluid state relations for your problem. If the algebra is straightforward, solve for what is *asked*. If the equations are complicated, e.g., nonlinear or too plentiful, use the Engineering Equation Solver (EES).
8. Report your solution clearly, with proper units listed and to the proper number of significant figures (usually two or three) that the overall uncertainty of the data will allow.

1.14 History and Scope of Fluid Mechanics

Like most scientific disciplines, fluid mechanics has a history of erratically occurring early achievements, then an intermediate era of steady fundamental discoveries in the eighteenth and nineteenth centuries, leading to the twentieth-century era of “modern practice,” as we self-centeredly term our limited but up-to-date knowledge. Ancient civilizations had enough knowledge to solve certain flow problems. Sailing ships with oars and irrigation systems were both known in prehistoric times. The Greeks produced quantitative information. Archimedes and Hero of Alexandria both postulated the parallelogram law for addition of vectors in the third century B.C. Archimedes (285–212 B.C.) formulated the laws of buoyancy and applied them to floating and submerged bodies, actually deriving a form of the differential calculus as part of the analysis. The Romans built extensive aqueduct systems in the fourth century B.C. but left no records showing any quantitative knowledge of design principles.

From the birth of Christ to the Renaissance there was a steady improvement in the design of such flow systems as ships and canals and water conduits but no recorded evidence of fundamental improvements in flow analysis. Then Leonardo da Vinci (1452–1519) derived the equation of conservation of mass in one-dimensional steady flow. Leonardo was an excellent experimentalist, and his notes contain accurate descriptions of waves, jets, hydraulic jumps, eddy formation, and both low-drag (streamlined) and high-drag (parachute) designs. A Frenchman, Edme Mariotte (1620–1684), built the first wind tunnel and tested models in it.

Problems involving the momentum of fluids could finally be analyzed after Isaac Newton (1642–1727) postulated his laws of motion and the law of viscosity of the linear fluids now called newtonian. The theory first yielded to the assumption of a "perfect" or frictionless fluid, and eighteenth-century mathematicians (Daniel Bernoulli, Leonhard Euler, Jean d'Alembert, Joseph-Louis Lagrange, and Pierre-Simon Laplace) produced many beautiful solutions of frictionless-flow problems. Euler developed both the differential equations of motion and their integrated form, now called the Bernoulli equation. D'Alembert used them to show his famous paradox: that a body immersed in a frictionless fluid has zero drag. These beautiful results amounted to overkill, since perfect-fluid assumptions have very limited application in practice and most engineering flows are dominated by the effects of viscosity. Engineers began to reject what they regarded as a totally unrealistic theory and developed the science of *hydraulics,* relying almost entirely on experiment. Such experimentalists as Chézy, Pitot, Borda, Weber, Francis, Hagen, Poiseuille, Darcy, Manning, Bazin, and Weisbach produced data on a variety of flows such as open channels, ship resistance, pipe flows, waves, and turbines. All too often the data were used in raw form without regard to the fundamental physics of flow.

At the end of the nineteenth century, unification between experimental *hydraulics* and theoretical *hydrodynamics* finally began. William Froude (1810–1879) and his son Robert (1846–1924) developed laws of model testing, Lord Rayleigh (1842–1919) proposed the technique of dimensional analysis, and Osborne Reynolds (1842–1912) published the classic pipe experiment in 1883 which showed the importance of the dimensionless Reynolds number named after him. Meanwhile, viscous-flow theory was available but unexploited, since Navier (1785–1836) and Stokes (1819–1903) had successfully added newtonian viscous terms to the equations of motion. The resulting Navier-Stokes equations were too difficult to analyze for arbitrary flows. Then, in 1904, a German engineer, Ludwig Prandtl (1875–1953), published perhaps the most important paper ever written on fluid mechanics. Prandtl pointed out that fluid flows with small viscosity, e.g., water flows and airflows, can be divided into a thin viscous layer, or *boundary layer,* near solid surfaces and interfaces, patched onto a nearly inviscid outer layer, where the Euler and Bernoulli equations apply. Boundary-layer theory has proved to be the single most important tool in modern flow analysis. The twentieth-century foundations for the present state of the art in fluid mechanics were laid in a series of broad-based experiments and theories by Prandtl and his two chief friendly competitors, Theodore von Kármán (1881–1963) and Sir Geoffrey I. Taylor (1886–1975). Many of the results sketched here from a historical point of view will, of course, be discussed in this textbook. More historical details can be found in Refs. 23 to 25.

Since the earth is 75 percent covered with water and 100 percent covered with air, the scope of fluid mechanics is vast and touches nearly every human endeavor. The sciences of meteorology, physical oceanography, and hydrology are concerned with naturally occurring fluid flows, as are medical studies of breathing and blood circulation. All transportation problems involve fluid motion, with well-developed specialties in aerodynamics of aircraft and rockets and in naval hydrodynamics of ships and submarines. Almost all our electric energy is developed either from water flow or from steam flow through turbine generators. All combustion problems involve fluid motion, as do the more classic problems of irrigation, flood control, water supply, sewage disposal, projectile motion, and oil and gas pipelines. The aim of this book is to present enough fundamental concepts and practical applications in fluid mechanics to prepare you to move smoothly into any of these specialized fields of the science of flow—and then be prepared to move out again as new technologies develop.

Problems

Most of the problems herein are fairly straightforward. More difficult or open-ended assignments are labeled with an asterisk as in Prob. 1.18. Problems labeled with an EES icon (for example, Prob. 2.62), will benefit from the use of the Engineering Equation Solver (EES), while problems labeled with a computer disk may require the use of a computer. The standard end-of-chapter problems 1.1 to 1.85 (categorized in the problem list below) are followed by fundamentals of engineering (FE) exam problems FE3.1 to FE3.10, and comprehensive problems C1.1 to C1.4.

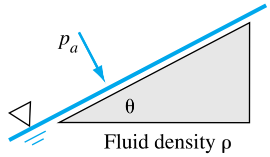
Problem Distribution

Section	Topic	Problems
1.1, 1.2, 1.3	Fluid-continuum concept	1.1–1.3
1.4	Dimensions, units, dynamics	1.4–1.20
1.5	Velocity field	1.21–1.23
1.6	Thermodynamic properties	1.24–1.37
1.7	Viscosity; no-slip condition	1.38–1.61
1.7	Surface tension	1.62–1.71
1.7	Vapor pressure; cavitation	1.72–1.75
1.7	Speed of sound; Mach number	1.76–1.78
1.8,9	Flow patterns, streamlines, pathlines	1.79–1.84
1.10	History of fluid mechanics	1.85

P1.1 A gas at 20°C may be considered *rarefied,* deviating from the continuum concept, when it contains less than 10^{12} molecules per cubic millimeter. If Avogadro's number is 6.023 E23 molecules per mole, what absolute pressure (in Pa) for air does this represent?

P1.2 Table A.6 lists the density of the standard atmosphere as a function of altitude. Use these values to estimate, crudely—say, within a factor of 2—the number of molecules of air in the entire atmosphere of the earth.

P1.3 For the triangular element in Fig. P1.3, show that a *tilted* free liquid surface, in contact with an atmosphere at pressure p_a, must undergo shear stress and hence begin to flow. *Hint:* Account for the weight of the fluid and show that a no-shear condition will cause horizontal forces to be out of balance.



P1.3

P1.4 A beaker approximates a right circular cone of diameter 7 in and height 9 in. When filled with liquid, it weighs 70 oz. When empty, it weighs 14 oz. Estimate the density of this liquid in both SI and BG units.

P1.5 The *mean free path* of a gas, ℓ, is defined as the average distance traveled by molecules between collisions. A proposed formula for estimating ℓ of an ideal gas is

$$\ell = 1.26\frac{\mu}{\rho\sqrt{RT}}$$

What are the dimensions of the constant 1.26? Use the formula to estimate the mean free path of air at 20°C and 7 kPa. Would you consider air *rarefied* at this condition?

P1.6 In the $\{MLT\Theta\}$ system, what is the dimensional representation of (*a*) enthalpy, (*b*) mass rate of flow, (*c*) bending moment, (*d*) angular velocity, (*e*) modulus of elasticity; (*f*) Poisson's ratio?

P1.7 A small village draws 1.5 acre · ft/day of water from its reservoir. Convert this average water usage to (*a*) gallons per minute and (*b*) liters per second.

P1.8 Suppose we know little about the strength of materials but are told that the bending stress σ in a beam is *proportional* to the beam half-thickness y and also depends upon the bending moment M and the beam area moment of inertia I. We also learn that, for the particular case $M = 2900$ in · lbf, $y = 1.5$ in, and $I = 0.4$ in^4, the predicted stress is 75 MPa. Using this information and dimensional reasoning only, find, to three significant figures, the only possible dimensionally homogeneous formula $\sigma = y\, f(M, I)$.

P1.9 The *kinematic viscosity* of a fluid is the ratio of viscosity to density, $\nu = \mu/\rho$. What is the only possible dimensionless group combining ν with velocity V and length L? What is the name of this grouping? (More information on this will be given in Chap. 5.)

P1.10 The Stokes-Oseen formula [18] for drag force F on a sphere of diameter D in a fluid stream of low velocity V, density ρ, and viscosity μ, is

$$F = 3\pi\mu DV + \frac{9\pi}{16}\rho V^2 D^2$$

Is this formula dimensionally homogeneous?

P1.11 Engineers sometimes use the following formula for the volume rate of flow Q of a liquid flowing through a hole of diameter D in the side of a tank:

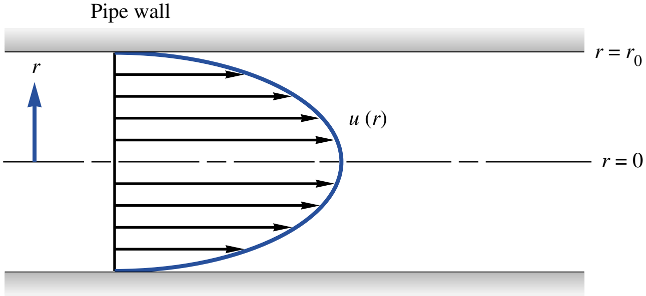
$$Q = 0.68\, D^2\sqrt{gh}$$

where g is the acceleration of gravity and h is the height of the liquid surface above the hole. What are the dimensions of the constant 0.68?

P1.12 For low-speed (laminar) steady flow through a circular pipe, as shown in Fig. P1.12, the velocity u varies with radius and takes the form

$$u = B\frac{\Delta p}{\mu}(r_0^2 - r^2)$$

where μ is the fluid viscosity and Δp is the pressure drop from entrance to exit. What are the dimensions of the constant B?



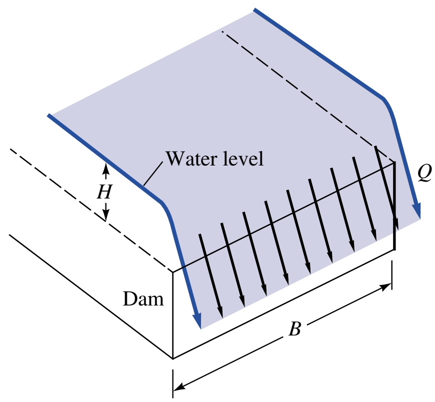
P1.12

P1.13 The efficiency η of a pump is defined as the (dimensionless) ratio of the power developed by the flow to the power required to drive the pump:

$$\eta = \frac{Q\Delta p}{\text{input power}}$$

where Q is the volume rate of flow and Δp is the pressure rise produced by the pump. Suppose that a certain pump develops a pressure rise of 35 lbf/in^2 when its flow rate is 40 L/s. If the input power is 16 hp, what is the efficiency?

***P1.14** Figure P1.14 shows the flow of water over a dam. The volume flow Q is known to depend only upon crest width B, acceleration of gravity g, and upstream water height H above the dam crest. It is further known that Q is proportional to B. What is the form of the only possible dimensionally homogeneous relation for this flow rate?



P1.14

P1.15 As a practical application of Fig. P1.14, often termed a sharp-crested weir, civil engineers use the following formula for flow rate: $Q \approx 3.3BH^{3/2}$, with Q in ft^3/s and B and H in feet. Is this formula dimensionally homogeneous? If not, try to explain the difficulty and how it might be converted to a more homogeneous form.

P1.16 Algebraic equations such as Bernoulli's relation, Eq. (1) of Ex. 1.3, are dimensionally consistent, but what about differential equations? Consider, for example, the boundary-layer x-momentum equation, first derived by Ludwig Prandtl in 1904:

$$\rho u\frac{\partial u}{\partial x} + \rho v\frac{\partial u}{\partial y} = -\frac{\partial p}{\partial x} + \rho g_x + \frac{\partial \tau}{\partial y}$$

where τ is the boundary-layer shear stress and g_x is the component of gravity in the x direction. Is this equation dimensionally consistent? Can you draw a general conclusion?

P1.17 The Hazen-Williams hydraulics formula for volume rate of flow Q through a pipe of diameter D and length L is given by

$$Q \approx 61.9\, D^{2.63}\left(\frac{\Delta p}{L}\right)^{0.54}$$

where Δp is the pressure drop required to drive the flow. What are the dimensions of the constant 61.9? Can this formula be used with confidence for various liquids and gases?

***P1.18** For small particles at low velocities, the first term in the Stokes-Oseen drag law, Prob. 1.10, is dominant; hence, $F \approx KV$, where K is a constant. Suppose a particle of mass m is constrained to move horizontally from the initial position $x = 0$ with initial velocity V_0. Show (*a*) that its velocity will decrease exponentially with time and (*b*) that it will stop after traveling a distance $x = mV_0/K$.

***P1.19** For larger particles at higher velocities, the quadratic term in the Stokes-Oseen drag law, Prob. 1.10, is dominant; hence, $F \approx CV^2$, where C is a constant. Repeat Prob. 1.18 to show that (*a*) its velocity will decrease as $1/(1 + CV_0 t/m)$ and (*b*) it will never quite stop in a finite time span.

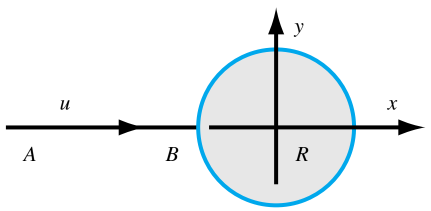
P1.20 A baseball, with $m = 145$ g, is thrown directly upward from the initial position $z = 0$ and $V_0 = 45$ m/s. The air drag on the ball is CV^2, as in Prob. 1.19, where $C \approx 0.0013\ \mathrm{N \cdot s^2/m^2}$. Set up a differential equation for the ball motion, and solve for the instantaneous velocity $V(t)$ and position $z(t)$. Find the maximum height z_{max} reached by the ball, and compare your results with the classical case of zero air drag.

P1.21 A velocity field is given by $\mathbf{V} = Kxt\mathbf{i} - Kyt\mathbf{j} + 0\mathbf{k}$, where K is a positive constant. Evaluate (*a*) $\nabla \cdot \mathbf{V}$ and (*b*) $\nabla \times \mathbf{V}$.

***P1.22** According to the theory of Chap. 8, as a uniform stream approaches a cylinder of radius R along the symmetry line AB in Fig. P1.22, the velocity has only one component:

$$u = U_\infty\left(1 - \frac{R^2}{x^2}\right) \quad \text{for } -\infty < x \le -R$$

where U_∞ is the stream velocity far from the cylinder. Using the concepts from Ex. 1.5, find (*a*) the maximum flow deceleration along AB and (*b*) its location.



P1.22

P1.23 Experiment with a faucet (kitchen or otherwise) to determine typical flow rates Q in m^3/h, perhaps timing the discharge of a known volume. Try to achieve an exit jet condition which is (*a*) smooth and round and (*b*) disorderly and fluctuating. Measure the supply-pipe diameter (look under the sink). For both cases, calculate the average flow velocity, $V_{avg} = Q/A_{cross\text{-}section}$ and the dimensionless Reynolds number of the flow, $\mathrm{Re} = \rho V_{avg} D/\mu$. Comment on your results.

P1.24 Air at 1 atm and 20°C has an internal energy of approximately 2.1 E5 J/kg. If this air moves at 150 m/s at an altitude $z = 8$ m, what is its total energy, in J/kg, relative to the datum $z = 0$? Are any energy contributions negligible?

P1.25 A tank contains 0.9 m^3 of helium at 200 kPa and 20°C. Estimate the total mass of this gas, in kg, (*a*) on earth and (*b*) on the moon. Also, (*c*) how much heat transfer, in MJ, is required to expand this gas at constant temperature to a new volume of 1.5 m^3?

P1.26 When we in the United States say a car's tire is filled "to 32 lb," we mean that its internal pressure is 32 lbf/in^2 above the ambient atmosphere. If the tire is at sea level, has a volume of 3.0 ft^3, and is at 75°F, estimate the total weight of air, in lbf, inside the tire.

P1.27 For steam at 40 lbf/in^2, some values of temperature and specific volume are as follows, from Ref. 13:

T, °F	400	500	600	700	800
v, ft^3/lbm	12.624	14.165	15.685	17.195	18.699

Is steam, for these conditions, nearly a perfect gas, or is it wildly nonideal? If reasonably perfect, find a least-squares† value for the gas constant R, in m^2/(s$^2 \cdot$ K), estimate the percent error in this approximation, and compare with Table A.4.

P1.28 Wet atmospheric air at 100 percent relative humidity contains saturated water vapor and, by Dalton's law of partial pressures,

$$p_{atm} = p_{dry\ air} + p_{water\ vapor}$$

Suppose this wet atmosphere is at 40°C and 1 atm. Calculate the density of this 100 percent humid air, and compare it with the density of dry air at the same conditions.

P1.29 A compressed-air tank holds 5 ft^3 of air at 120 lbf/in^2 "gage," that is, above atmospheric pressure. Estimate the energy, in ft-lbf, required to compress this air from the atmosphere, assuming an ideal isothermal process.

P1.30 Repeat Prob. 1.29 if the tank is filled with compressed *water* instead of air. Why is the result thousands of times less than the result of 215,000 ft · lbf in Prob. 1.29?

***P1.31** EES The density of (fresh) water at 1 atm, over the temperature range 0 to 100°C, is given in Table A.1. Fit these values to a least-squares† equation of the form $\rho = a + bT + cT^2$, with T in °C, and estimate its accuracy. Use your formula to compute the density of water at 45°C, and compare your result with the accepted experimental value of 990.1 kg/m^3.

† The concept of "least-squares" error is very important and should be learned by everyone.

P1.32 A blimp is approximated by a prolate spheroid 90 m long and 30 m in diameter. Estimate the weight of 20°C gas within the blimp for (*a*) helium at 1.1 atm and (*b*) air at 1.0 atm. What might the *difference* between these two values represent (see Chap. 2)?

***P1.33** Experimental data for the density of mercury versus pressure at 20°C are as follows:

p, atm	1	500	1,000	1,500	2,000
ρ, kg/m^3	13,545	13,573	13,600	13,625	13,653

Fit this data to the empirical state relation for liquids, Eq. (1.22), to find the best values of B and n for mercury. Then, assuming the data are nearly isentropic, use these values to estimate the speed of sound of mercury at 1 atm and compare with Table 9.1.

P1.34 If water occupies 1 m^3 at 1 atm pressure, estimate the pressure required to reduce its volume by 5 percent.

P1.35 In Table A.4, most common gases (air, nitrogen, oxygen, hydrogen) have a specific heat ratio $k \approx 1.40$. Why do argon and helium have such high values? Why does NH_3 have such a low value? What is the lowest k for any gas that you know of?

P1.36 The isentropic bulk modulus B of a fluid is defined as the isentropic change in pressure per fractional change in density:

$$B = \rho\left(\frac{\partial p}{\partial \rho}\right)_s$$

What are the dimensions of B? Using theoretical $p(\rho)$ relations, estimate the bulk modulus of (*a*) N_2O, assumed to be an ideal gas, and (*b*) water, at 20°C and 1 atm.

P1.37 A near-ideal gas has a molecular weight of 44 and a specific heat $c_v = 610$ J/(kg · K). What are (*a*) its specific heat ratio, k, and (*b*) its speed of sound at 100°C?

P1.38 In Fig. 1.6, if the fluid is glycerin at 20°C and the width between plates is 6 mm, what shear stress (in Pa) is required to move the upper plate at 5.5 m/s? What is the Reynolds number if L is taken to be the distance between plates?

P1.39 Knowing μ for air at 20°C from Table 1.4, estimate its viscosity at 500°C by (*a*) the power law and (*b*) the Sutherland law. Also make an estimate from (*c*) Fig. 1.5. Compare with the accepted value of $\mu \approx 3.58$ E-5 kg/m · s.

***P1.40** For liquid viscosity as a function of temperature, a simplification of the log-quadratic law of Eq. (1.31) is *Andrade's equation* [11], $\mu \approx A \exp(B/T)$, where (A, B) are curve-fit constants and T is absolute temperature. Fit this relation to the data for water in Table A.1 and estimate the percent error of the approximation.

P1.41 Some experimental values of the viscosity of argon gas at 1 atm are as follows:

T, K	300	400	500	600	700	800
μ, kg/(m · s)	2.27 E-5	2.85 E-5	3.37 E-5	3.83 E-5	4.25 E-5	4.64 E-5

Fit these value to either (*a*) a power law or (*b*) the Sutherland law, Eq. (1.30).

P1.42 Experimental values for the viscosity of helium at 1 atm are as follows:

T, K	200	400	600	800	1000	1200
μ, kg/(m · s)	1.50 E-5	2.43 E-5	3.20 E-5	3.88 E-5	4.50 E-5	5.08 E-5

Fit these values to either (*a*) a power law or (*b*) the Sutherland law, Eq. (1.30).

***P1.43** Yaws et al. [34] suggest the following curve-fit formula for viscosity versus temperature of organic liquids:

$$\log_{10} \mu \approx A + \frac{B}{T} + CT + DT^2$$

with T in absolute units. (*a*) Can this formula be criticized on dimensional grounds? (*b*) Disregarding (*a*), indicate analytically how the curve-fit constants A, B, C, D could be found from N data points (μ_i, T_i) using the method of least squares. Do not actually carry out a calculation.

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, $9.3 < \nu < 12.5$ mm^2/s at 100°C. SAE 30 oil density can also vary ±2 percent from the tabulated value of 891 kg/m^3. Consider the following data for an acceptable grade of SAE 30 oil:

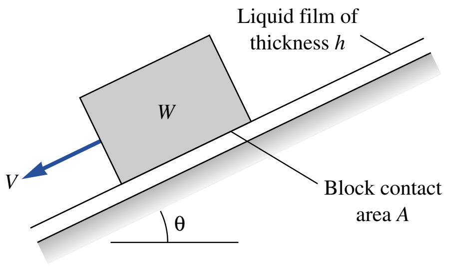
T, °C	0	20	40	60	80	100
μ, kg/(m · s)	2.00	0.40	0.11	0.042	0.017	0.0095

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.

P1.46 Find the terminal velocity of the block in Fig. P1.45 if the block mass is 6 kg, $A = 35$ cm^2, $\theta = 15°$, and the film is 1-mm-thick SAE 30 oil at 20°C.

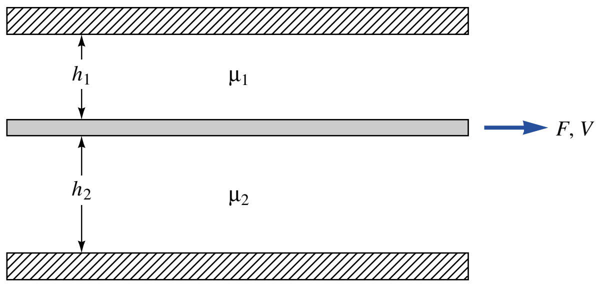
P1.47 A shaft 6.00 cm in diameter is being pushed axially through a bearing sleeve 6.02 cm in diameter and 40 cm long. The clearance, assumed uniform, is filled with oil



P1.45

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?



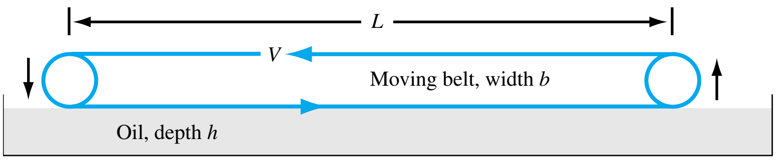
P1.48

P1.49 The shaft in Prob. 1.47 is now fixed axially and rotated inside the sleeve at 1500 r/min. Estimate (*a*) the torque (N · m) and (*b*) the power (kW) required to rotate the shaft.

P1.50 An amazing number of commercial and laboratory devices have been developed to measure the viscosity of fluids, as described in Ref. 27. The concentric rotating shaft of Prob. 1.49 is an example of a *rotational viscometer*. 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. Derive a theoretical relation for the viscosity of the clearance fluid, μ, in terms of these parameters.

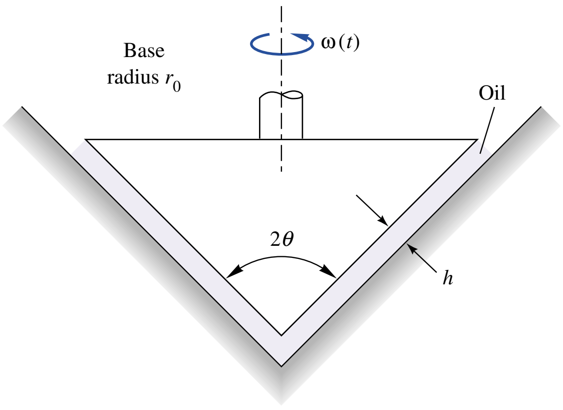
P1.51 Use the theory of Prob. 1.50 (or derive an ad hoc expression if you like) for a shaft 8 cm long, rotating at 1200 r/min, with $r_i = 2.00$ cm and $r_o = 2.05$ cm. If the measured torque is 0.293 N · m, what is the fluid viscosity? Suppose that the uncertainties of the experiment are as follows: L (±0.5 mm), M (±0.003 N · m), Ω (±1 percent), and r_i or r_o (±0.02 mm). What is the uncertainty in the measured viscosity?

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?



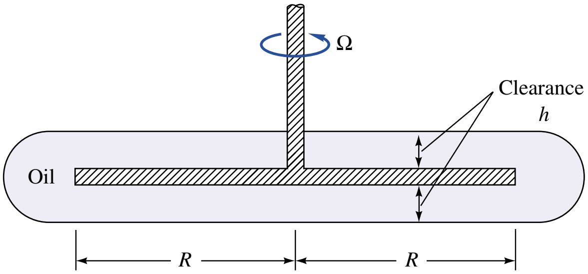
P1.52

***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

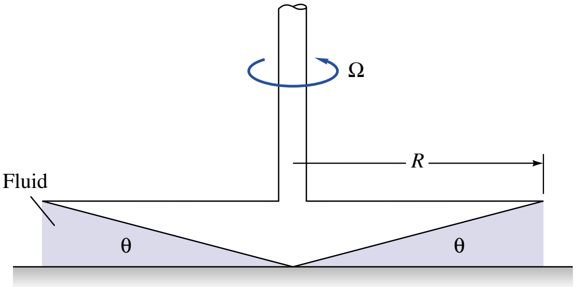
***P1.54** A disk of radius R rotates at an angular velocity Ω inside a disk-shaped container filled with oil of viscosity μ, as shown in Fig. P1.54. Assuming a linear velocity profile and neglecting shear stress on the outer disk edges, derive a formula for the viscous torque on the disk.



P1.54

***P1.55** The device in Fig. P1.54 is called a *rotating disk viscometer* [27]. Suppose that $R = 5$ cm and $h = 1$ mm. If the torque required to rotate the disk at 900 r/min is 0.537 N · m, what is the viscosity of the fluid? If the uncertainty in each parameter (M, R, h, Ω) is ± 1 percent, what is the overall uncertainty in the viscosity?

***P1.56** The device in Fig. P1.56 is called a *cone-plate viscometer* [27]. 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 cone-plate viscometer of Fig. P1.56, suppose that $R = 6$ cm and $\theta = 3°$. If the torque required to rotate the cone at 600 r/min is 0.157 N · m, what is the viscosity of the fluid? If the uncertainty in each parameter (M, R, Ω, θ) is ± 1 percent, what is the overall uncertainty in the viscosity?

***P1.58** The laminar-pipe-flow example of Prob. 1.12 can be used to design a *capillary viscometer* [27]. 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 [27]. 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 For Prob. 1.52 suppose that $P = 0.1$ hp when $V = 6$ ft/s, $L = 4.5$ ft, $b = 22$ in, and $h = 7/8$ in. Estimate the viscosity of the oil, in kg/(m · s). If the uncertainty in each parameter (P, L, b, h, V) is ± 1 percent, what is the overall uncertainty in the viscosity?

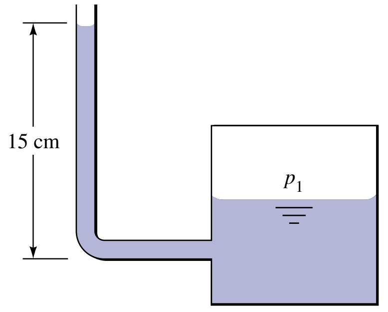
***P1.61** An air-hockey puck has a mass of 50 g and is 9 cm in diameter. When placed on the air table, a 20°C air film, of 0.12-mm thickness, forms under the puck. The puck is struck with an initial velocity of 10 m/s. Assuming a linear velocity distribution in the air film, how long will it take the 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 which produced the velocity profiles in Fig. 1.13 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. (1.37) by making a force balance on the fluid interface in Fig. 1.9*c*.

P1.64 At 60°C the surface tension of mercury and water is 0.47 and 0.0662 N/m, respectively. What capillary height changes will occur in these two fluids when they are in contact with air in a clean glass tube of diameter 0.4 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 (see Prob. 1.64). Calculate the true fluid height in the tube and the percent error due to capillarity if the fluid is (*a*) water and (*b*) mercury.

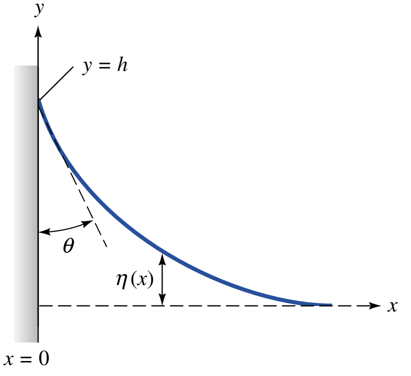


P1.65

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 Experiment with a capillary tube, perhaps borrowed from the chemistry department, to verify, in clean water, the rise due to surface tension predicted by Example 1.9. Add small amounts of liquid soap to the water, and report to the class whether detergents significantly lower the surface tension. What practical difficulties do detergents present?

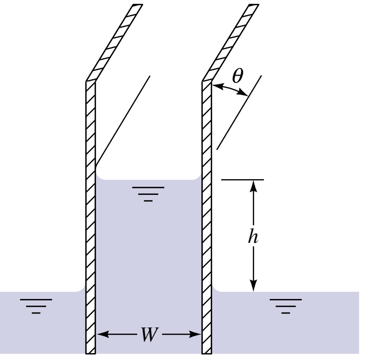
***P1.68** Make an analysis of the shape $\eta(x)$ of the water-air interface near a plane wall, as in Fig. P1.68, assuming that the slope is small, $R^{-1} \approx d^2\eta/dx^2$. Also assume that the pressure difference across the interface is balanced by the specific weight and the interface height, $\Delta p \approx \rho g \eta$. 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 EES 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 A propeller is tested in a water tunnel at 20°C as in Fig. 1.12*a*. The lowest pressure on the blade can be estimated by a form of Bernoulli's equation (Ex. 1.3):

$$p_{min} \approx p_0 - \tfrac{1}{2}\rho V^2$$

where $p_0 = 1.5$ atm and V = tunnel velocity. If we run the tunnel at $V = 18$ m/s, can we be sure that there will be no cavitation? If not, can we change the water temperature and avoid cavitation?

P1.75 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?

P1.76 An airplane flies at 555 mi/h. At what altitude in the standard atmosphere will the airplane's Mach number be exactly 0.8?

***P1.77** 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 Examine the photographs in Figs. 1.12*a*, 1.13, 5.2*a*, 7.14*a*, and 9.10*b* and classify them according to the boxes in Fig. 1.14.

***P1.80** A two-dimensional steady velocity field is given by $u = x^2 - y^2$, $v = -2xy$. Derive the streamline pattern and sketch a few streamlines in the upper half plane. *Hint:* The differential equation is exact.

P1.81 Repeat Ex. 1.10 by letting the velocity components increase linearly with time:

$$\mathbf{V} = Kxt\mathbf{i} - Kyt\mathbf{j} + 0\mathbf{k}$$

Find and sketch, for a few representative times, the instantaneous streamlines. How do they differ from the steady flow lines in Ex. 1.10?

P1.82 A velocity field is given by $u = V\cos\theta$, $v = V\sin\theta$, and $w = 0$, where V and θ are constants. Derive a formula for the streamlines of this flow.

***P1.83** A two-dimensional unsteady velocity field is given by $u = x(1 + 2t)$, $v = y$. Find the equation of the time-varying streamlines which all pass through the point (x_0, y_0) at some time t. Sketch a few of these.

***P1.84** Repeat Prob. 1.83 to find and sketch the equation of the *pathline* which passes through (x_0, y_0) at time $t = 0$.

P1.85 Do some reading and report to the class on the life and achievements, especially vis-à-vis fluid mechanics, of

(*a*) Evangelista Torricelli (1608–1647)
(*b*) Henri de Pitot (1695–1771)
(*c*) Antoine Chézy (1718–1798)
(*d*) Gotthilf Heinrich Ludwig Hagen (1797–1884)
(*e*) Julius Weisbach (1806–1871)
(*f*) George Gabriel Stokes (1819–1903)
(*g*) Moritz Weber (1871–1951)
(*h*) Theodor von Kármán (1881–1963)
(*i*) Paul Richard Heinrich Blasius (1883–1970)
(*j*) Ludwig Prandtl (1875–1953)
(*k*) Osborne Reynolds (1842–1912)
(*l*) John William Strutt, Lord Rayleigh (1842–1919)
(*m*) Daniel Bernoulli (1700–1782)
(*n*) Leonhard Euler (1707–1783)

Fundamentals of Engineering Exam Problems

FE1.1 The absolute viscosity μ of a fluid is primarily a function of
(*a*) Density, (*b*) Temperature, (*c*) Pressure, (*d*) Velocity, (*e*) Surface tension

FE1.2 If a uniform solid body weighs 50 N in air and 30 N in water, its specific gravity is
(*a*) 1.5, (*b*) 1.67, (*c*) 2.5, (*d*) 3.0, (*e*) 5.0

FE1.3 Helium has a molecular weight of 4.003. What is the weight of 2 m^3 of helium at 1 atm and 20°C?
(*a*) 3.3 N, (*b*) 6.5 N, (*c*) 11.8 N, (*d*) 23.5 N, (*e*) 94.2 N

FE1.4 An oil has a kinematic viscosity of 1.25 E-4 m^2/s and a specific gravity of 0.80. What is its dynamic (absolute) viscosity in kg/(m · s)?
(*a*) 0.08, (*b*) 0.10, (*c*) 0.125, (*d*) 1.0, (*e*) 1.25

FE1.5 Consider a soap bubble of diameter 3 mm. If the surface tension coefficient is 0.072 N/m and external pressure is 0 Pa gage, what is the bubble's internal gage pressure?
(*a*) −24 Pa, (*b*) +48 Pa, (*c*) +96 Pa, (*d*) +192 Pa, (*e*) −192 Pa

FE1.6 The only possible dimensionless group which combines velocity V, body size L, fluid density ρ, and surface tension coefficient σ is
(*a*) $L\rho\sigma/V$, (*b*) $\rho VL^2/\sigma$, (*c*) $\rho\sigma V^2/L$, (*d*) $\sigma LV^2/\rho$, (*e*) $\rho LV^2/\sigma$

FE1.7 Two parallel plates, one moving at 4 m/s and the other fixed, are separated by a 5-mm-thick layer of oil of specific gravity 0.80 and kinematic viscosity 1.25 E-4 m^2/s. What is the average shear stress in the oil?
(*a*) 80 Pa, (*b*) 100 Pa, (*c*) 125 Pa, (*d*) 160 Pa, (*e*) 200 Pa

FE1.8 Carbon dioxide has a specific heat ratio of 1.30 and a gas constant of 189 J/(kg · °C). If its temperature rises from 20 to 45°C, what is its internal energy rise?
(*a*) 12.6 kJ/kg, (*b*) 15.8 kJ/kg, (*c*) 17.6 kJ/kg, (*d*) 20.5 kJ/kg, (*e*) 25.1 kJ/kg

FE1.9 A certain water flow at 20°C has a critical cavitation number, where bubbles form, $Ca \approx 0.25$, where $Ca = 2(p_a - p_{vap})/\rho V^2$. If p_a = 1 atm and the vapor pressure is 0.34 pounds per square inch absolute (psia), for what water velocity will bubbles form?
(*a*) 12 mi/h, (*b*) 28 mi/h, (*c*) 36 mi/h, (*d*) 55 mi/h, (*e*) 63 mi/h

FE1.10 A steady incompressible flow, moving through a contraction section of length L, has a one-dimensional average velocity distribution given by $u \approx U_0(1 + 2x/L)$. What is its convective acceleration at the end of the contraction, $x = L$?
(*a*) U_0^2/L, (*b*) $2U_0^2/L$, (*c*) $3U_0^2/L$, (*d*) $4U_0^2/L$, (*e*) $6U_0^2/L$

Comprehensive Problems

C1.1 Sometimes equations can be developed and practical problems can be solved by knowing nothing more than the dimensions of the key parameters in the problem. For example, consider the heat loss through a window in a building. Window efficiency is rated in terms of "*R* value" which has units of (ft^2 · h · °F)/Btu. A certain manufacturer advertises a double-pane window with an *R* value of 2.5. The same company produces a triple-pane window with an *R* value of 3.4. In either case the window dimensions are 3 ft by 5 ft. On a given winter day, the temperature difference between the inside and outside of the building is 45°F.

(*a*) Develop an equation for the amount of heat lost in a given time period Δt, through a window of area A, with *R* value R, and temperature difference ΔT. How much heat (in Btu) is lost through the double-pane window in one 24-h period?

(*b*) How much heat (in Btu) is lost through the triple-pane window in one 24-h period?

(*c*) Suppose the building is heated with propane gas, which costs \$1.25 per gallon. The propane burner is 80 percent efficient. Propane has approximately 90,000 Btu of available energy per gallon. In that same 24-h period, how much money would a homeowner save per window by installing triple-pane rather than double-pane windows?

(*d*) Finally, suppose the homeowner buys 20 such triple-pane windows for the house. A typical winter has the equivalent of about 120 heating days at a temperature difference of 45°F. Each triple-pane window costs \$85 more than the double-pane window. Ignoring interest and inflation, how many years will it take the homeowner to make up the additional cost of the triple-pane windows from heating bill savings?

C1.2 When a person ice skates, the surface of the ice actually melts beneath the blades, so that he or she skates on a thin sheet of water between the blade and the ice.

(*a*) Find an expression for total friction force on the bottom of the blade as a function of skater velocity V, blade length L, water thickness (between the blade and the ice) h, water viscosity μ, and blade width W.

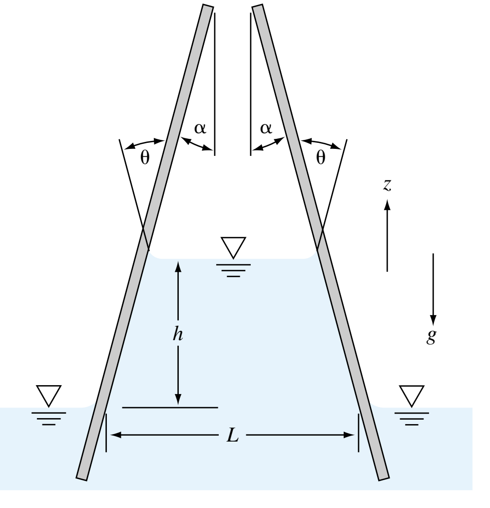
(*b*) Suppose an ice skater of total mass m is skating along at a constant speed of V_0 when she suddenly stands stiff with her skates pointed directly forward, allowing herself to coast to a stop. Neglecting friction due to air resistance, how far will she travel before she comes to a stop? (Remember, she is coasting on *two* skate blades.) Give your answer for the total distance traveled, x, as a function of V_0, m, L, h, μ, and W.

(*c*) Find x for the case where V_0 = 4.0 m/s, m = 100 kg, L = 30 cm, W = 5.0 mm, and h = 0.10 mm. Do you think our assumption of negligible air resistance is a good one?

C1.3 Two thin flat plates, tilted at an angle α, are placed in a tank of liquid of known surface tension Υ and contact angle θ, as shown in Fig. C1.3. At the free surface of the liquid in the tank, the two plates are a distance L apart and have width b into the page. The liquid rises a distance h between the plates, as shown.

(a) What is the total upward (z-directed) force, due to surface tension, acting on the liquid column between the plates?

(b) If the liquid density is ρ, find an expression for surface tension Υ in terms of the other variables.



C1.3