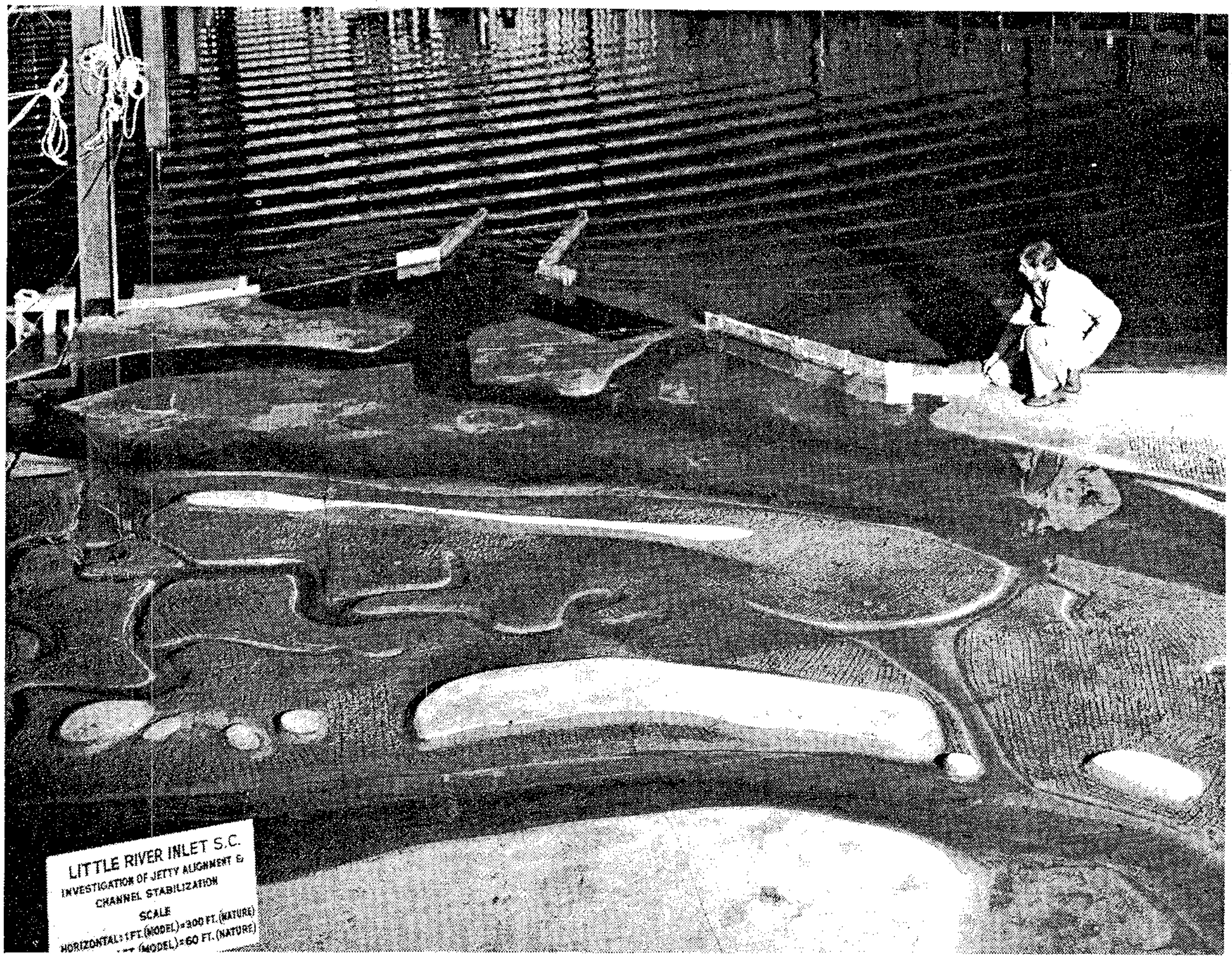

Fig. 5.10 Hydraulic model of a barrier-beach inlet at Little River, South Carolina. Such models of necessity violate geometric similarity and do not model the Reynolds number of the prototype inlet. (*Courtesy of U.S. Army Engineer Waterways Experiment Station.*)

5.6 INVENTIVE USE OF THE DATA

The methods of dimensional analysis discussed here allow one to organize both theory and experiment efficiently. The parameters arrived at are customary and traditional: Reynolds number, Froude number, drag coefficient, etc. They are not necessarily the best parameters for a given task, and sometimes they do not give a clear indication of what is happening physically in an experiment. The remedy for this is to regroup the parameters until the particular problem under investigation is most clearly revealed.

As an example of a regrouping procedure, consider Fig. 5.3*a* for the drag coefficient of a sphere in a uniform stream. This figure is a classic and is reproduced in nearly every textbook on fluid mechanics, but it is a drag-oriented figure. One is supposed to be given the fluid, the diameter, and the velocity, and hence compute the Reynolds number, read the drag coefficient, and compute the sphere drag. Suppose instead that the drag is known but the fluid velocity is not. Then, since V is contained in both C_D and Re, one must iterate back and forth on the chart in Fig. 5.3*a* until the proper velocity is found. With luck the iteration procedure converges. Consider the following numerical example.

EXAMPLE 5.8 A 0.1-ft-diameter steel sphere ($\rho_s = 15.2$ slugs/ft^3) is dropped in water [$\rho = 1.94$ slugs/ft^3, $\mu = 0.000021$ slug/(ft · s)] until it reaches terminal velocity or zero acceleration. From the sphere data in Fig. 5.3*a*, compute the terminal velocity of the falling sphere in feet per second.

solution At terminal velocity, the net weight of the sphere equals the drag; hence the drag is known in this problem

$$D = W_{\text{net}} = (\rho_s - \rho)g\,\frac{\pi}{6}\,d^3$$

$$= (15.2 - 1.94 \text{ slugs/ft}^3)(32.2 \text{ ft/s}^2)\,\frac{\pi}{6}\,(0.1 \text{ ft})^3 = 0.224 \text{ lb}$$

We can compute that portion of C_D and Re which excludes the unknown velocity

$$C_D = \frac{D}{\frac{1}{2}\rho(\pi/4)d^2V^2} = \frac{0.224 \text{ lb}}{1.94(\pi/8)(0.1 \text{ ft})^2V^2} = \frac{29.4}{(V \text{ ft/s})^2}$$

$$\text{Re} = \frac{\rho V d}{\mu} = \frac{(1.94 \text{ slugs/ft}^3)(V)(0.1 \text{ ft})}{2.1 \times 10^{-5} \text{ slug/(ft}\cdot\text{s)}} = 9240V \text{ ft/s}$$

Now we will just have to guess an initial velocity V to get started on the iteration.

Guess $V = 1.0$ ft/s; then Re $= 9240(1.0) = 9240$. From Fig. 5.3*a* read $C_D \approx 0.38$; then $V \approx (29.4/C_D)^{1/2} = 8.8$ ft/s. Now try again with this new guess.

Guess $V = 8.8$ ft/s, Re $= 9240(8.8) = 81{,}000$. From Fig. 5.3*a* read $C_D \approx 0.52$, $V \approx (29.4/0.52)^{1/2} = 7.5$ ft/s. One more try will give pretty good convergence.

Guess $V = 7.5$ ft/s, Re $= 9240(7.5) = 69{,}000$. From Fig. 5.3*a* read $C_D \approx 0.51$, $V \approx (29.4/0.51)^{1/2} = 7.6$ ft/s. To the accuracy of the figure

$$V_{\text{term}} \approx 7.6 \text{ ft/s} \qquad \textit{Ans.}$$

The iteration in Example 5.8 converged to a proper terminal velocity. However, near the transition point Re $\approx 3 \times 10^5$, convergence is erratic, and the iteration may oscillate and not settle down. The process of computation is also laborious. The remedy is to regroup the pi products so that only one contains the unknown velocity. It happens that we found a velocity-free parameter in Example 5.5

$$C'_F = \frac{D\rho}{\mu^2} = \frac{D}{\mu\nu} = \frac{\pi}{8}\,C_D\,\text{Re}^2 \tag{5.59}$$

This is a perfectly good parameter, if rather uncommon, and a plot of C'_F versus Re is equivalent in every way to a plot of C_D versus Re. Such a regrouped plot is shown in Fig. 5.11. If D, ρ, μ, and d are known, this plot can be read directly for the velocity. It also shows the actual shape of the variation of sphere drag with velocity. Sphere drag increases rapidly with velocity up to transition, where there is a slight drop, after which drag increases faster than ever. This is in contrast to Fig. 5.3*a*, which might be misread to imply that sphere drag decreases with velocity and drops dramatically at transition.

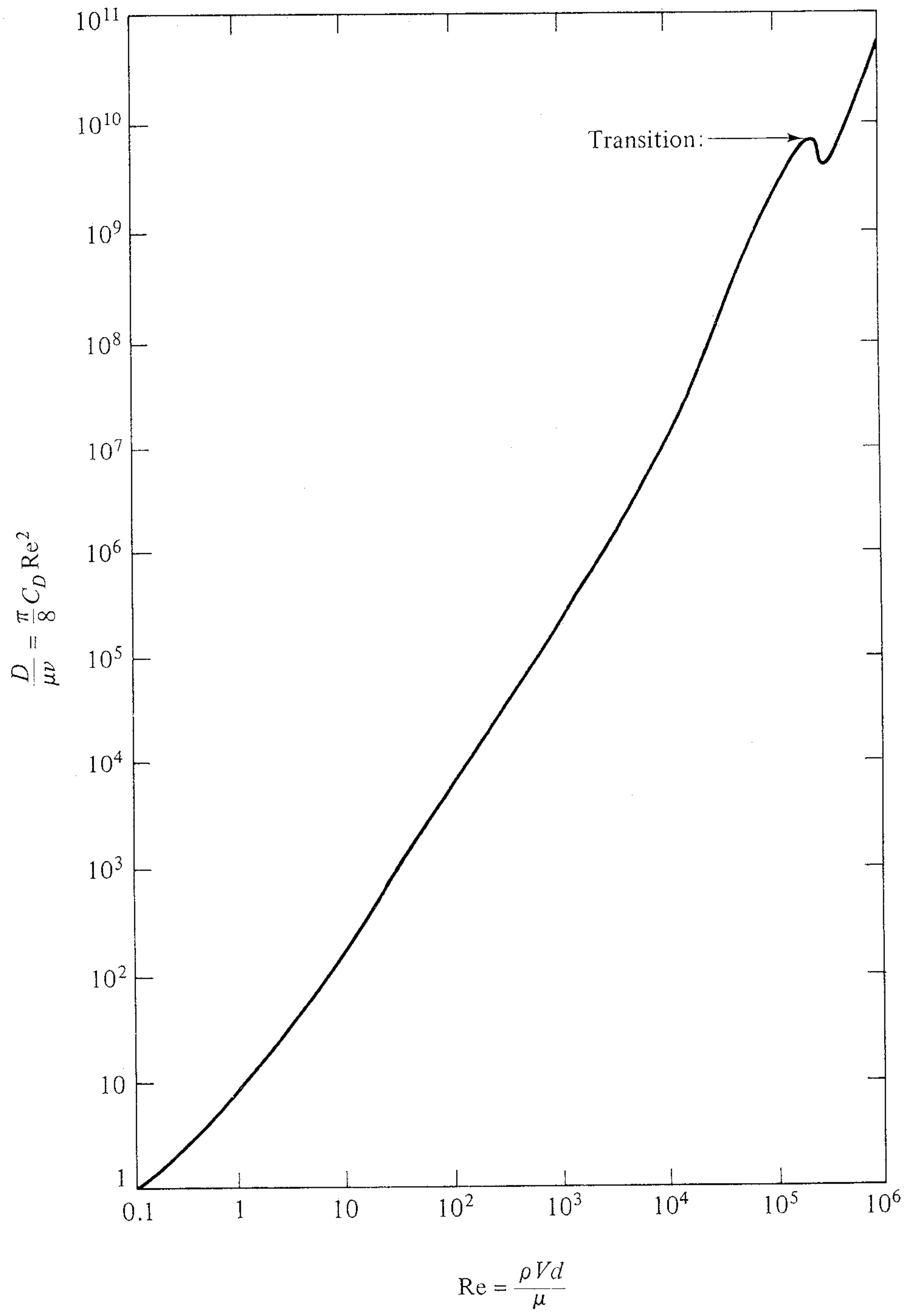

Fig. 5.11 Crossplot of sphere-drag data from Fig. 5.3*a* to isolate diameter and velocity.

EXAMPLE 5.9 Repeat Example 5.8, using the regrouped chart, Fig. 5.11.

solution We must repeat the calculation of the net weight to establish that $D = W_{\mathrm{net}} =$ 0.224 lb. But now we can go directly to the new drag coefficient

$$C'_F = \frac{(0.224 \text{ lb})(1.94 \text{ slugs/ft}^3)}{[2.1 \times 10^{-5} \text{ slug/(ft} \cdot \text{s)}]^2} = 9.8 \times 10^8 = \frac{D\rho}{\mu^2}$$

Now enter Fig. 5.11 and read Re $\approx$ 70,000. Then the desired velocity is

$$V = \frac{\mu \, \mathrm{Re}}{\rho d} = \frac{[2.1 \times 10^{-5} \text{ slug/(ft} \cdot \text{s)}](70{,}000)}{(1.94 \text{ slugs/ft}^3)(0.1 \text{ ft})}$$

or

$$V_{\text{term}} = 7.6 \text{ ft/s} \qquad \textit{Ans.}$$

No iteration is required.

This example should illustrate the power and glory of regrouping dimensionless variables to display certain effects convenient to a particular analysis. For a one-shot calculation, it would take too much time to draw the new regrouped plot (Fig. 5.11), and one might as well hack about with Fig. 5.3*a* for a single calculation. In general, however, it is up to you, the analyst, to display your dimensionless results in the best manner for the purpose desired. There is no need to constantly mimic the traditional parameters unless they are convenient to the problem at hand.

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PROBLEMS

Circled ones CIVE relevant

5.1 Which of the two dimensionless forms of the falling-body relation in Fig. 5.1 is more effective, (*a*) or (*b*)? Explain the reasons for your choice.

5.2 A 5-cm-diameter sphere is tested in water at 20°C and a velocity of 4 m/s and found to have a drag of 6.5 N. What will the velocity and drag of a 3-m diameter weather balloon moving in air at 20°C and 1 atm be under similar conditions?

5.3 An 8-cm-diameter sphere is tested in SAE 30 oil at 20°C at velocities of 1, 2, and 3 m/s and found to have drag forces of 1.92, 6.40, and 13.2 N, respectively. Estimate the drag force if the same sphere is tested in glycerin at 20°C and a velocity of 6 m/s.

5.4 Nondimensionalize Bernoulli's equation (5.6) by using the parameters ρ, U, and L to define dimensionless variables p^*, V^*, and z^*. How many dimensionless parameters appear? How many different formulations $p^* = f(V^*, z^*)$ can you write?

5.5 For a particle moving in a circle, assume that the centripetal acceleration a is a function of velocity V and radius R. Without using any calculus, i.e., by pure dimensional reasoning, show that the proper form is $a = (\text{const})(V^2)/R$.

5.6 The velocity of sound a of a gas varies with pressure p and density ρ. Show by dimensional reasoning that the proper form must be $a = (\text{const})(p/\rho)^{1/2}$.

5.7 The speed of propagation C of a capillary wave in deep water is known to be a function only of density ρ, wavelength λ, and surface tension Υ. Use the power-product method to derive the single dimensionless parameter which governs this problem. For the same density and wavelength, how does the propagation speed change if the surface tension is doubled?

5.8 The excess pressure Δp inside a bubble is known to be a function of the surface tension and the radius. By dimensional reasoning determine how the excess pressure will vary if we double (*a*) the radius and (*b*) the surface tension.

5.9 An airplane has a characteristic length of 125 ft and is designed to fly at 200 mi/h at 10,000 ft standard altitude. The drag coefficient as defined by Eq. (5.2) is measured with a small model and found to be 0.011. What is the horsepower required to drive the prototype airplane?

5.10 It is desired to measure the drag on an airplane whose velocity is 400 mi/h. Is it feasible to test a one-twentieth-scale model of the plane in a wind tunnel at the same pressure and temperature to determine the prototype drag coefficient?

5.11 A one-twentieth-scale model of a submarine is tested at 200 ft/s in a wind tunnel using sea-level standard air. What is the prototype speed in 20°C seawater for dynamic similarity? If the model drag is 1 lbf, what is the prototype drag?

Problems 5.12 to 5.30 may be solved either by the power-product method or by the pi theorem.

5.12 The period of swing T of a simple pendulum is assumed to be a function of its length L, bob mass m, the acceleration of gravity, and the swing angle θ. Use dimensional analysis to rewrite this relationship as a dimensionless function. Did anything interesting happen? What happens to the period if the length is doubled and all other parameters remain the same?

5.13 Repeat Prob. 5.12 assuming that there is a significant damping effect due to the surrounding fluid of density ρ and viscosity μ.

5.14 The period of oscillation T of a water surface wave is assumed to be a function of density ρ, wavelength λ, depth h, gravity g, and surface tension Υ. Rewrite this relationship in dimensionless form. What results if Υ is negligible? – shallow wave theory?

basis of all pump operation

5.15 The power input P to a centrifugal pump is assumed to be a function of volume flux Q, impeller diameter D, rotational rate Ω, and the density ρ and viscosity μ of the fluid. Rewrite this as a dimensionless relationship.

5.16 Extend Prob. 5.15 to write the relationship between the pressure rise $\Delta p/\rho$ across the pump and the same five variables Q, D, Ω, ρ, and μ in dimensionless form. What happens if viscosity is negligible?

5.17 The resistance force F of a surface ship is a function of its length L, velocity V, gravity g, and the density ρ and viscosity μ of the water. Rewrite in dimensionless form.

5.18 The lift force F on a missile is a function of its length L, velocity V, diameter D, angle of attack α, and the density ρ, viscosity μ, and speed of sound a of the air. Rewrite this relation in dimensionless form.

5.19 The period T of vibration of a beam is a function of its length L, area moment of inertia I, modulus of elasticity E, density ρ, and Poisson's ratio σ. Rewrite this relation in dimensionless form. What further reduction can we make if E and I can only occur in the product form EI?

5.20 The torque M on an axial flow turbine is a function of fluid density ρ, rotor diameter D, angular rotation rate Ω, and volume flux Q. Rewrite in dimensionless form. If it is known that M is proportional to Q for a particular turbine, how would M vary with Ω and D for that turbine?

5.21 The period of heave oscillation T of a simple spar buoy (see Prob. 2.113) varies with its cross-sectional area A, its mass m, gravity g, and the water density ρ. Rewrite in dimensionless form. What happens to T if the area is doubled? Instrument buoys should have a very long period to avoid wave resonance. Sketch a design which would have long period.

5.22 According to elementary kinetic theory (Ref. 7 of Chap. 1), the thermal conductivity k of a gas is a function of its density ρ, gas constant R, mean free path λ, and absolute temperature T. Rewrite in dimensionless form. If R is doubled with other parameters constant, how will k change?

5.23 The heat-transfer rate per unit area q to a wall from a fluid flow is a function of temperature difference ΔT, velocity U, and the physical properties of the fluid ρ, μ, c_p, and k. Write this relation in dimensionless form if it is known that q is proportional to ΔT.

5.24 The heat-transfer rate per unit area q to a body from a fluid in natural or gravitational convection is a function of temperature difference ΔT, gravity g, body length L, and three fluid properties: kinematic viscosity ν, conductivity k, and thermal expansion coefficient β. Rewrite in dimensionless form if it is known that g and β appear only as the product $g\beta$.

5.25 It is known from experiment that the fluid velocity u very near a wall in turbulent flow varies only with distance y from the wall, wall shear stress τ_w, and the fluid properties ρ and μ. Rewrite this relation in dimensionless form.

5.26 The flow velocity u very near a rotating disk varies only with disk angular velocity ω, local radius R, distance z from the disk, and kinematic viscosity ν. Rewrite this relation in dimensionless form.

Blast wall design?

5.27 The pressure difference Δp across an explosion or blast wave is a function of distance r from the blast center, time t, speed of sound a of the medium, and total energy E in the blast. Rewrite this relation in dimensionless form (see Ref. 18, chap. 4, for further details of blast-wave scaling). How does Δp change if E is doubled?

good test question

5.28 A weir is an obstruction in a channel used to measure the flow rate, as in Fig. 10.12*b*. The volume flux Q varies with gravity g, weir width b, and the upstream water height H above the weir crest. If it is known that Q is proportional to b, use dimensional analysis to find a unique relationship for $Q = f(g, b, H)$.

5.29 The size d of droplets produced by a liquid spray nozzle is thought to depend upon the nozzle diameter D, jet velocity U, and the properties of the liquid ρ, μ, and Υ. Rewrite this relation in dimensionless form.

5.30 In flow past a flat plate the boundary-layer thickness δ is a function of stream velocity U, distance x downstream from the plate leading edge, and fluid properties ρ and μ. Rewrite this relation in dimensionless form.

5.31 Nondimensionalize the energy equation (4.75) and its boundary conditions (4.62), (4.63), and (4.70) by defining $T^* = T/T_0$, where T_0 is the inlet temperature, assumed constant. Use other dimensionless variables as needed from Eqs. (5.32). Isolate all dimensionless parameters you find and relate them to the list given in Table 5.2.

5.32 In natural-convection problems the variation of density due to temperature difference ΔT creates an important buoyancy term in the momentum equation (5.30). To first-order accuracy the density variation would be $\rho \approx \rho_0(1 - \beta\,\Delta T)$, where β is the thermal-expansion coefficient. The momentum equation thus becomes

$$\rho_0 \frac{d\mathbf{V}}{dt} = -\nabla(p + \rho_0 g z) + \rho_0 \beta\,\Delta T g \mathbf{k} + \mu \nabla^2 \mathbf{V}$$

where we have assumed that z is "up." Nondimensionalize this equation using Eqs. (5.32) and relate the parameters you find to the list in Table 5.2.

5.33 The differential equation of salt conservation for flowing seawater is

$$\frac{\partial S}{\partial t} + u\frac{\partial S}{\partial x} + v\frac{\partial S}{\partial y} + w\frac{\partial S}{\partial z} = \kappa\left(\frac{\partial^2 S}{\partial x^2} + \frac{\partial^2 S}{\partial y^2} + \frac{\partial^2 S}{\partial z^2}\right)$$

where κ is a (constant) coefficient of diffusion, with typical units of square meters per second, and S is the salinity in parts per thousand. Nondimensionalize this equation and discuss any parameters which appear.

5.34 The differential equation for compressible inviscid flow of a gas in the xy plane is

$$\frac{\partial^2 \phi}{\partial t^2} + \frac{\partial}{\partial t}(u^2 + v^2) + (u^2 - a^2)\frac{\partial^2 \phi}{\partial x^2} + (v^2 - a^2)\frac{\partial^2 \phi}{\partial y^2} + 2uv\frac{\partial^2 \phi}{\partial x\,\partial y} = 0$$

where ϕ is the velocity potential and a is the (variable) speed of sound of the gas. Nondimensionalize this relation using a reference length L and the inlet speed of sound a_0 as parameters for defining dimensionless variables.

Problems 5.35 to 5.42 can make use of Figs. 5.2 and 5.3.

5.35 A sphere of diameter 3 cm is moving in ethyl alcohol at 20°C and a speed of 50 cm/s. What will be its drag in newtons? What increase in speed would cause the drag to be quadrupled?

5.36 A steel (SG = 7.86) sphere 1 cm in diameter is dropped into water at 20°C. What will its terminal fall velocity be in meters per second? *Hint:* Use Fig. 5.3*a*.

5.37 Repeat Prob. 5.36 if the fluid is glycerin at 20°C.

5.38 A steel sphere dropped into SAE 30 oil at 20°C is found to have a terminal velocity of 1 cm/s. What is its diameter in millimeters?

5.39 A vertical 6-in-diameter piling supports a dock above fresh water 12 ft deep. If the water-current velocity is 3 ft/s, what is the drag force in pounds force on the piling?

5.40 A 1-in-diameter telephone wire is mounted in air at 20°C and has a natural vibration frequency of 12 Hz. What wind velocity in feet per second will cause the wire to sing? At this condition what will the average drag force per unit wire length be?

5.41 A ship is towing a sonar array which approximates a submerged cylinder 1 ft in diameter and 30 ft long with its axis normal to the direction of tow. If the tow speed is 12 knots (1 knot = 1.69 ft/s), estimate the horsepower required to tow this cylinder. What will be the frequency of vortices shed from the cylinder?

5.42 A flagpole is 10 cm in diameter and is found to have its minimum drag coefficient at a wind speed of 10 m/s. Estimate the average roughness of the surface of the flagpole in millimeters.

5.43 We want to know the drag of a blimp moving in 20°C air at 20 ft/s. If a one-thirtieth scale model is tested in water at 20°C, what should the water velocity be? If the measured model drag is 700 lbf, what is the drag on the prototype blimp and what horsepower is required to propel it?

5.44 The pressure drop across a model orifice meter is 0.1 lbf/in^2 when it is tested in 20°C water at an approach velocity of 4.5 ft/s. What will be the pressure drop in pounds force per square inch of the prototype meter be if it is 4 times larger and operates in SAE 30 oil at 20°C with an approach velocity which is dynamically similar?

5.45 A prototype water pump has an impeller diameter of 2 ft and is designed to pump 12 ft^3/s at 750 r/min. A 1-ft-diameter model pump is tested in 20°C air at 1800 r/min, and Reynolds-number effects are found to be negligible. For similar conditions, what will the volume flux of the model be in cubic feet per second? If the model pump requires 0.082 hp to drive it, what horsepower is required for the prototype?

5.46 It is found by experiment that 1 lbf of dynamite will cause a shock overpressure of 100 lbf/in^2 at a radius of 4 ft and a time of 3.5 ms after the explosion. For dynamically similar conditions, at what radius and time will 1 ton (2000 lbf) of dynamite cause the same overpressure? (See Prob. 5.27 for a list of variables.)

5.47 A certain fluid of specific gravity 0.92 in a tube of 3 cm diameter is found to have a capillary rise of 2 mm. What will be its capillary rise in a 5-cm-diameter tube? For what diameter will the capillary rise be 1 cm?

5.48 A torpedo 8 m below the surface in 20°C seawater cavitates at a speed of 21 m/s when atmospheric pressure is 101 kPa. If Reynolds-number and Froude-number effects are negligible, at what speed will it cavitate when running at a depth of 20 m? At what depth should it be to avoid cavitation at 30 m/s?

5.49 A one-fifth-scale model automobile is tested in a wind tunnel in the same air properties as the prototype. The prototype velocity is 80 km/h. For dynamically similar conditions the model drag is 450 N. What are the drag of the prototype automobile and the power in kilowatts required to overcome this drag?

5.50 A rotary mixer is to be designed for stirring ethyl alcohol. Tests with a one-fourth-scale model in SAE 30 oil indicate most efficient mixing at 1770 r/min. What should the speed of the prototype mixer be in revolutions per minute?

5.51 The equation defining an ellipsoid is

$$\left(\frac{x}{a}\right)^2 + \left(\frac{y}{b}\right)^2 + \left(\frac{z}{c}\right)^2 = 1$$

where a, b, and c are reference lengths. If the prototype ellipsoid has $a = 5$ m, $b = 3$ m, and $c = 1$ m, what should b and c be for the model ellipsoid if a is 1 m?

5.52 Tests with water at 20°C flowing through a $\frac{1}{2}$-in-diameter pipe 100 ft long show a pressure drop of 13 lbf/in^2 at a flow rate of 12 gal/min (1 gal = 231 in^3). Under dynamically similar conditions, if it is known that Δp is proportional to pipe length, what will be Δp in pounds force per square inch and Q in gallons per minute for gasoline flowing in a 6-in pipe 50 mi long? *Hint:* This problem requires a dimensional analysis similar to Example 5.2, with density and pipe length as additional variables.

5.53 A dam spillway is to be tested using Froude scaling with a one-thirtieth-scale model. The model flow has an average velocity of 0.6 m/s and a volume flux of 0.05 m^3/s. What will the velocity and flux of the prototype be? If the measured force on a certain part of the model is 1.5 N, what will the corresponding force on the prototype be?

5.54 A prototype spillway has a characteristic velocity of 3 m/s and a characteristic length of 10 m. A small model is constructed using Froude scaling. What is the minimum scale ratio of the model which will ensure that its minimum Weber number is 100? Both flows use water at 20°C.

5.55 An East coast estuary has a tidal period of 12.42 h (the semidiurnal lunar tide) and tidal currents of approximately 80 cm/s. If a one-five-hundredth-scale model is constructed with tides driven by a pump and storage apparatus, what should the period of the model tides be and what model current speeds are expected?

5.56 A prototype ship is 400 ft long and has a wetted area of 30,000 ft^2. A one-eightieth-scale model is tested in a tow tank according to Froude scaling at speeds of 1.3, 2.0, and 2.7 knots (1 knot = 1.689 ft/s). The measured friction drag of the model at these speeds is 0.11, 0.24, and 0.41 lbf, respectively. What are the three prototype speeds? What is the estimated prototype friction drag at these speeds if we correct for the Reynolds-number discrepancy by extrapolation?

5.57 An airplane is designed to fly at 575 mi/h at 35,000 ft U.S. standard altitude. If a one-tenth-scale model is tested in a pressurized wind tunnel at 68°F, what should the tunnel pressure in pounds force per square inch absolute be to scale both the Reynolds and Mach numbers correctly?

5.58 A prototype ocean-platform piling is expected to encounter currents of 150 cm/s and waves of 12 s period and 3 m height. If a one-fifteenth-scale model is tested in a wave channel, what current speed, wave period, and wave height should be encountered by the model?

5.59 The yawing moment on a torpedo control surface is tested on a one-eighth-scale model in a water tunnel at 20 m/s using Reynolds scaling. If the model measured moment is 14 N · m, what will the prototype moment be under similar conditions?

5.60 A one-twelfth-scale model of a weir (see Fig. 10.12*b*) has a measured flow rate of 1.9 ft^3/s when the upstream water height is $h = 6$ in. Use the results of Prob. 5.28 to predict the prototype flow rate when $h = 3$ ft. *Hint:* Be careful, these conditions are not geometrically similar.

5.61 An axial compressor is intended to pump helium at 1200 r/min. A one-third-scale model is tested in air at 600 r/min and exhibits a flow rate of 6 ft^3/s, a pressure rise of 145 Pa, and a power input of 1.0 kW. For dynamically similar conditions compute Q, Δp, and the power input for the prototype. Neglect Mach- and Reynolds-number effects and assume sea-level conditions.

5.62 A one-fifteenth-scale model of a parachute has a drag of 450 lbf when tested at 20 ft/s in a water tunnel. If Reynolds-number effects are negligible, estimate the terminal fall velocity at 5000 ft standard altitude of a parachutist using the prototype if chute and chutist together weigh 160 lbf. Neglect the drag coefficient of the woman.

5.63 A model venturi flowmeter tested in water shows a pressure drop of 0.7 lbf/in^2 when the approach velocity is 12 ft/s.

Reynolds-number effects are negligible. A prototype flowmeter is used to measure gasoline at a flow rate of 2400 gal/min (1 gal = 231 in^3). If the prototype pressure transducer is most accurate at 2.5 lbf/in^2 Δp, what should the upstream pipe diameter be?

5.64 A one-fortieth-scale model of a ship's propeller is tested in a tow tank at 1200 r/min and exhibits a power output of 1.4 (ft · lbf)/s. According to Froude scaling laws, what should the revolutions per minute and horsepower output of the prototype propeller be under dynamically similar conditions?

5.65 A one-tenth-scale model of a supersonic wing tested at 700 m/s in air at 20°C and 1 atm shows a pitching moment of 0.25 kN · m. If Reynolds-number effects are negligible, what will the pitching moment of the prototype wing be flying at the same Mach number at 8 km standard altitude?