17A Objectives

After completing this section, I can

- ✓ discuss the difference between fluids and nonfluids.
- ✓ define the dimensions of density and pressure and state the units used to measure them.
- ✓ discuss how pressure is generated within incompressible and compressible fluids.
- ✓ describe how Pascal's principle explains the operation of simple hydraulic machines.
- ✓ describe how manometers and barometers operate.
- ✓ use Archimedes' principle to compute the buoyant force acting on a submerged object.
- ✓ describe the stability of a submerged object by using the relative positions of its centers of mass and buoyancy.
- ✓ explain the function of a hydrometer.

17A Section Review

1. **a.** Name and briefly describe the two subsections of fluid mechanics.
   b. In what fundamental way does fluid mechanics differ from the mechanics you have studied prior to this chapter?
2. **a.** Using qualitative terms, how does fluid pressure vary horizontally through a fluid?
   b. How does it vary vertically?
3. What three factors determine the static pressure in any fluid at a given depth (or height)?
4. What determines the force a fluid exerts against a surface?
5. What two factors determine the buoyant force exerted on an object submerged in a fluid?
6. How deep (in meters and feet) must a diver go (in fresh water) in order to experience two atmospheres of pressure? (Recall that a diver experiences 1 atm at the water's surface.) State your answer to two significant digits.
7. Assuming that atmospheric pressure at sea level is 1.00 atm, what would be atmospheric pressure at the level of the Dead Sea (altitude: −400. m)? Ignore difference in pressure due to variation of temperature.
8. A block of solid oak (30.0 cm × 40.0 cm × 50.0 cm) floats in fresh water. What percentage of the block's volume is *not* under water?

17B HYDRODYNAMICS: FLUIDS IN MOTION

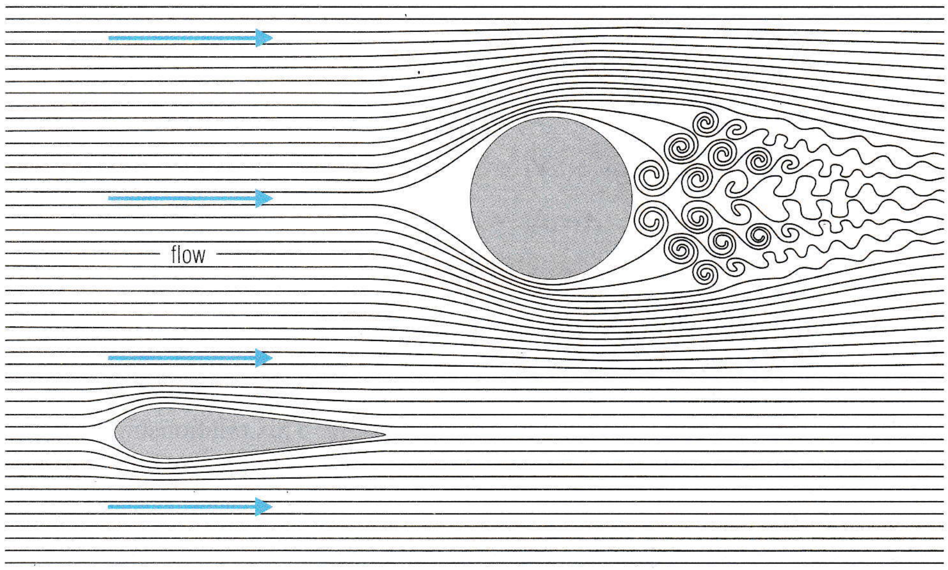
17.13 Ideal Fluids

The concepts that you have been studying in hydrostatics are fairly simple. Hydrodynamics, in contrast, is one of the most complicated areas of physics. To simplify the study, we must establish the concept of the **ideal fluid**. In the case of an ideal fluid, it is assumed that

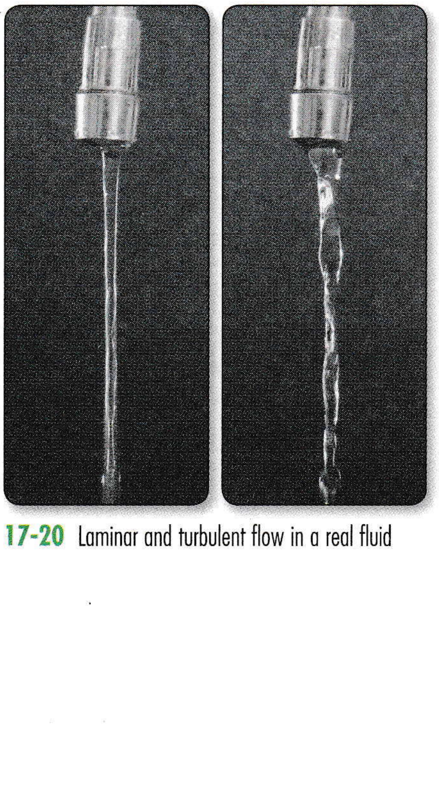
- the fluid flows smoothly;
- the velocity of the fluid does not change with time at a fixed location in the fluid path;
- the density of the fluid is constant (the fluid, whatever its density, is incompressible);
- friction has no effect on fluid flow.

These assumptions are only approximately true for real fluids, and mainly for liquids.

The first assumption, the idea that ideal fluids flow smoothly, means that every particle passing through a given point follows the same path. Such a path is called a **streamline**. Streamlines have no physical reality, but they are useful in visualizing fluid flow. If the streamlines are continuous, then the flow is smooth, or **laminar**. If the streamlines have discontinuities (bumps, twists, or turns), then the flow is **turbulent** and thus requires much more complex modeling. Several streamlines can define a **flow tube**. A flow tube may be an actual cylindrical pipe, or it may be a small volume within a larger volume of flowing fluid. The fluid particles do not cross the boundaries of a flow tube. For the purposes of hydrodynamic studies, a flow tube defines the boundaries of a physical system.



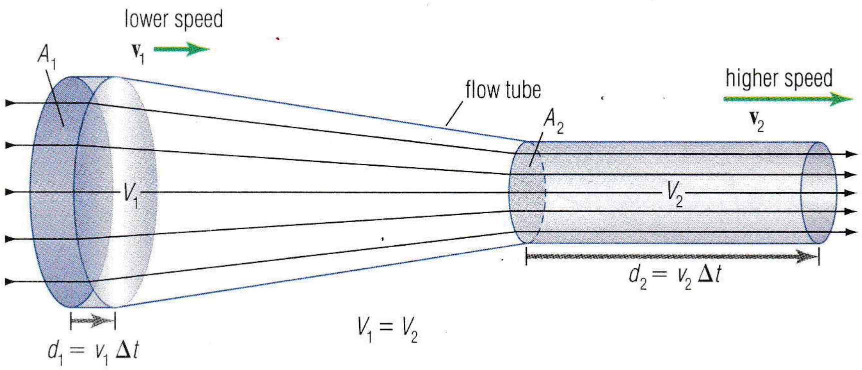
17-19 Streamlines around various objects showing laminar and turbulent flow



17-20 Laminar and turbulent flow in a real fluid

The second assumption establishes that the velocity of the fluid at any one location is constant with time. However, it does *not* mean that fluid velocity cannot be different at various points within a body of flowing fluid at the same time.

The third assumption is that fluids are incompressible. This, combined with the law of conservation of mass, requires that the rate of volume and mass flow into a segment of a flow tube equals the rate of volume and mass flow out of the flow tube segment. That is, if 1 L of fluid flows into one end of a flow tube in 1 s, 1 L of fluid must flow out the other end in the same second. If this were not true, then either some mass would disappear in the tube or some mass would be created in the tube.



17-21 A flow tube showing how a constriction affects flow rate

17.14 Flow Continuity

The volume of fluid flowing into a flow tube segment is shaped roughly like a cylinder. The base of the cylinder is the cross section of the flow tube at the beginning of the segment, which has area A_1. The "height" of the cylinder is the length traveled by a particle of the fluid in time Δt. This distance is equal to the velocity in that segment of the flow tube multiplied by the time interval. The volume flowing into the flow tube segment is

$$V_1 = A_1 v_1 \Delta t.$$

Similarly, the volume of fluid flowing out of the segment in time Δt is

$$V_2 = A_2 v_2 \Delta t.$$

These volumes must be equal.

$$V_1 = V_2$$

$$A_1 v_1 \Delta t = A_2 v_2 \Delta t$$

$$A_1 v_1 = A_2 v_2 \qquad (17.11)$$

Equation 17.11 is called the **equation of flow continuity**. Notice that in order for this equation to hold true, lengths of flow tube segments with smaller cross sections must have higher velocities than lengths with larger cross sections. Otherwise the product of A and v would not remain constant. This relationship between area and velocity is evident in nature: a river flows rapidly in areas where it is narrow; but as the river widens, its flow rate decreases.

EXAMPLE 17-5

Slow with the Flow: Flow Continuity

A fluid flows through a level pipe at a speed of 4.00 m/s at a point where the pipe's cross-sectional area is 10.0 cm². How fast will it flow where the pipe's area is 20.0 cm²?

Solution:

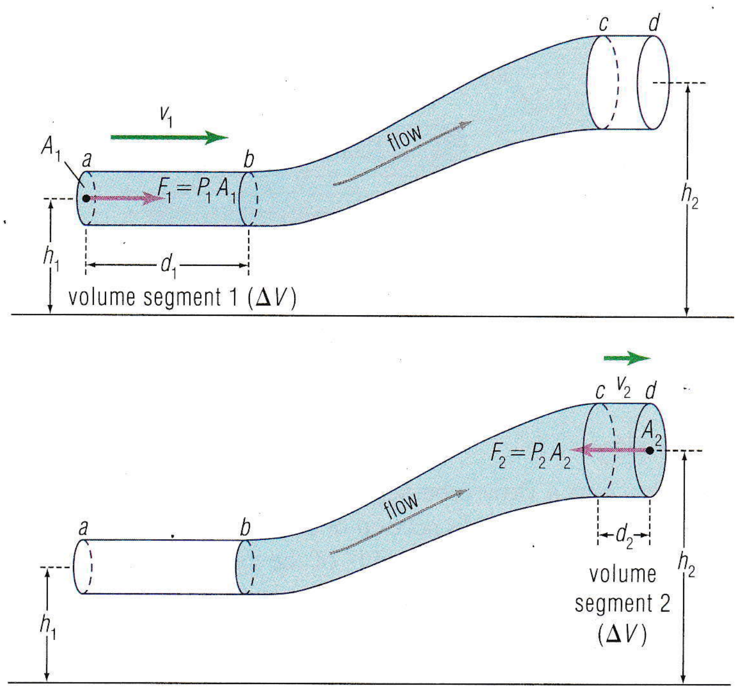
$$A_1 v_1 = A_2 v_2$$

$$v_2 = \frac{A_1 v_1}{A_2} = \frac{(10.0\ \text{cm}^2)(4.00\ \text{m/s})}{20.0\ \text{cm}^2}$$

$$v_2 = 2.00\ \text{m/s}$$

Problem-Solving Strategy 17.4

It is permissible to use different metric systems in one calculation as long as the units cancel. This often occurs in simple proportional calculations.



17-22 A fluid gains potential energy by moving against gravity.

17.15 Bernoulli's Principle

Consider the energy and work involved in moving a segment of fluid between *a* and *c* (the colored portion) to the volume between *b* and *d* in Figure 17-22. This is equivalent to transferring a volume of fluid, ΔV, from a height h_1, velocity v_1, and area A_1 to a height h_2, velocity v_2, and area A_2. The change in kinetic energy is

$$\Delta K = \tfrac{1}{2}mv_2^2 - \tfrac{1}{2}mv_1^2.$$

Since the density of the fluid is the mass divided by the volume of the fluid, $\rho = m/\Delta V$, then $m = \rho\Delta V$ and

$$\Delta K = \tfrac{1}{2}\rho\Delta V v_2^2 - \tfrac{1}{2}\rho\Delta V v_1^2. \tag{17.12}$$

The change in mechanical potential energy is due in this case to the change in height of the fluid sample above an arbitrary reference height,

$$\Delta U = m|g|h_2 - m|g|h_1, \text{ and}$$
$$\Delta U = \rho\Delta V|g|h_2 - \rho\Delta V|g|h_1. \tag{17.13}$$

Since we assumed that the flow is not turbulent and there are no friction or viscosity effects in or on the fluid, all the work done on the segment of fluid by all other nonconservative forces just changes the total mechanical energy of the fluid. In other words, according to the work-energy theorem,

$$W_{\text{ncf}} = \Delta K + \Delta U. \tag{17.14}$$

The total work done *on* the fluid is equal to the work done by the fluid force on the left side of the first volume segment ($\mathbf{F}_1$) plus the work done by the fluid force on the right side of the second volume segment ($\mathbf{F}_2$). The work of each force is calculated from the product of the force and its displacement through each segment of fluid. So the work of the first force is

$$W_1 = F_1\Delta d_1,$$

since the force and displacement of the fluid are oriented in the same direction. The fluid in the second segment is still moving to the right, but the external fluid force exerted on it is oriented to the left. Therefore, the work on the second fluid segment is

$$W_2 = -F_2\Delta d_2.$$

From the definition of pressure, we know that

$$F_1 = P_1A_1, \text{ and}$$
$$F_2 = P_2A_2.$$

Substituting these expressions for force into the respective work equations gives us

$$W_1 = P_1A_1\Delta d_1, \text{ and}$$
$$W_2 = -P_2A_2\Delta d_2.$$

The arbitrarily small fixed volume ΔV is the product of the area of each fluid segment and the arbitrarily small fixed displacement of the fluid in the flow tube at each segment.

$$\Delta V = A_1\Delta d_1 = A_2\Delta d_2$$

The variable ΔV is used for this derivation of Bernoulli's equation because it is intended to represent an arbitrarily small fixed volume of fluid rather than a definite volume change.

In the context of work and potential energy, ΔU means the change of mechanical potential energy as in Chapter 9 rather than the change of internal energy as in Chapter 16.

In this discussion, the symbol Δd is used to represent an arbitrarily small fixed displacement rather than a specific distance.

We can now substitute ΔV for $A_1\Delta d_1$ and $A_2\Delta d_2$ in the work equations. The work done by each of the fluid forces is then as follows:

$$W_1 = P_1\Delta V$$

$$W_2 = -P_2\Delta V$$

The work done by nonconservative forces is

$$W_{ncf} = W_1 + W_2, \text{ and}$$

$$W_{ncf} = P_1\Delta V - P_2\Delta V. \qquad (17.15)$$

Substituting Equations 17.15, 17.12, and 17.13 for W_{ncf}, ΔK, and ΔU in the work-energy theorem (Equation 17.14), respectively, gives the following:

$$W_{ncf} = \Delta K + \Delta U$$

$$P_1\Delta V - P_2\Delta V = (\tfrac{1}{2}\rho\Delta V v_2^2 - \tfrac{1}{2}\rho\Delta V v_1^2) + (\rho\Delta V g h_2 - \rho\Delta V g h_1)$$

Dividing each term by ΔV gives

$$P_1 - P_2 = \tfrac{1}{2}\rho v_2^2 - \tfrac{1}{2}\rho v_1^2 + \rho g h_2 - \rho g h_1.$$

Rearranging to group terms associated with each fluid segment, we obtain

$$P_1 + \tfrac{1}{2}\rho v_1^2 + \rho g h_1 = P_2 + \tfrac{1}{2}\rho v_2^2 + \rho g h_2. \qquad (17.16)$$

Daniel Bernoulli (1700–82) was a Swiss mathematician who studied many different scientific topics. He is best known for his work in hydrodynamics, vibrating strings, and probability.

Equation 17.16 is called **Bernoulli's equation**.

17.16 Bernoulli's Principle and Constant Velocity

There are two special cases of Bernoulli's equation. One is the case where the cross section of the pipe, and therefore the velocity, does not change. Then

$$v_1 = v_2 = v.$$

Substituting this into Bernoulli's equation:

$$P_1 + \cancel{\tfrac{1}{2}\rho v^2} + \rho g h_1 = P_2 + \cancel{\tfrac{1}{2}\rho v^2} + \rho g h_2$$

$$P_1 + \rho g h_1 = P_2 + \rho g h_2$$

Problem-Solving Strategy 17.5

In an ideal flow tube, if the flow cross section remains constant, then fluid pressure depends only on the height of the fluid above the reference height, according to Bernoulli's equation.

The difference in pressure ($\Delta P = P_2 - P_1$) depends only on the difference in depth in the fluid ($\Delta h = h_2 - h_1$). This is the same relationship that determines the change of hydrostatic pressure.

17.17 Bernoulli's Principle and Constant Height

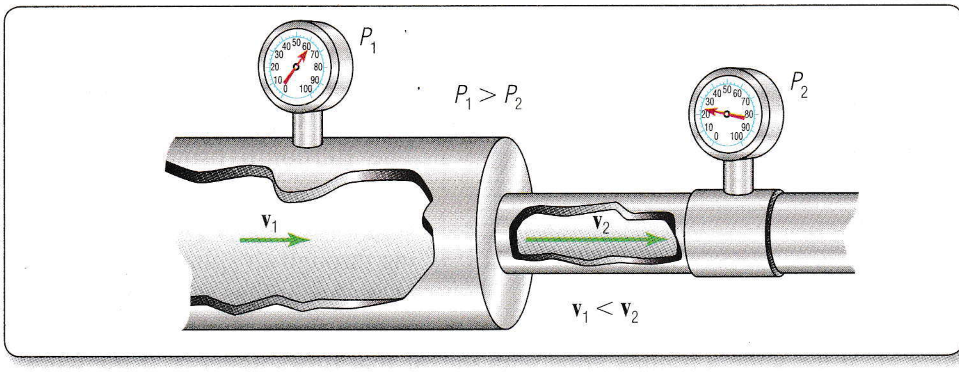
The other special case is one in which the fluid remains at the same elevation. Then,

$$h_1 = h_2 = h.$$

Substituting this into Equation 17.16:

$$P_1 + \tfrac{1}{2}\rho v_1^2 + \cancel{\rho g h} = P_2 + \tfrac{1}{2}\rho v_2^2 + \cancel{\rho g h}$$

$$P_1 + \tfrac{1}{2}\rho v_1^2 = P_2 + \tfrac{1}{2}\rho v_2^2$$



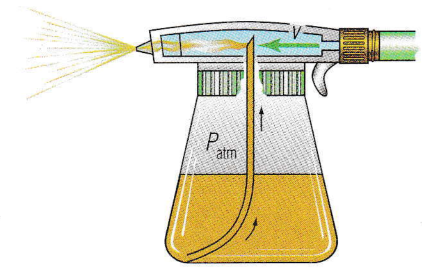
17-23 The faster flow has lower pressure.

This equation shows that in order to maintain the equality, if the velocity of the fluid increases in a segment of flow tube, the corresponding pressure must decrease, and vice versa.

You can tell which parts of a fluid are moving faster by studying the streamlines. Faster portions have smaller areas; therefore, the streamlines are diagrammatically closer together. Since faster portions have lower pressure, closely spaced streamlines also indicate lower pressure.

Problem-Solving Strategy 17.6

In an ideal flow tube, if the height remains constant, fluid pressure will increase when fluid speed decreases and vice versa, according to Bernoulli's equation.



17-24 This sprayer works because air moving through a restriction lowers the pressure, drawing the liquid up the tube. This phenomenon, called the *Venturi effect*, is the consequence of the Bernoulli principle and flow continuity.

EXAMPLE 17-6

Pressure and Speed: Bernoulli's Principle

Water flowing through a level pipe has a pressure of 2.50×10^4 Pa when its speed is 1.00 m/s. The water flows through a constriction into a smaller pipe. What is its pressure when its speed increases to 3.00 m/s?

Solution:

$$P_1 + \tfrac{1}{2}\rho v_1^2 = P_2 + \tfrac{1}{2}\rho v_2^2$$

$$P_2 = P_1 + \tfrac{1}{2}\rho v_1^2 - \tfrac{1}{2}\rho v_2^2 = P_1 + \tfrac{1}{2}\rho(v_1^2 - v_2^2)$$

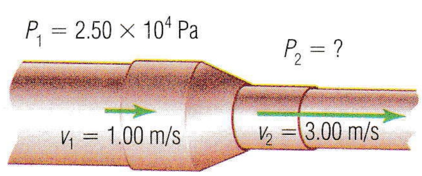
$$P_2 = 2.50 \times 10^4\ \text{Pa} + \tfrac{1}{2}(1.00 \times 10^3\ \text{kg/m}^3)\ [(1.00\ \text{m/s})^2 - (3.00\ \text{m/s})^2]$$

$$P_2 = 2.50 \times 10^4\ \text{Pa} - 40\underline{0}0\ \text{Pa}$$

$$P_2 = 2.10 \times 10^4\ \text{Pa}$$

$$P_2 < P_1$$

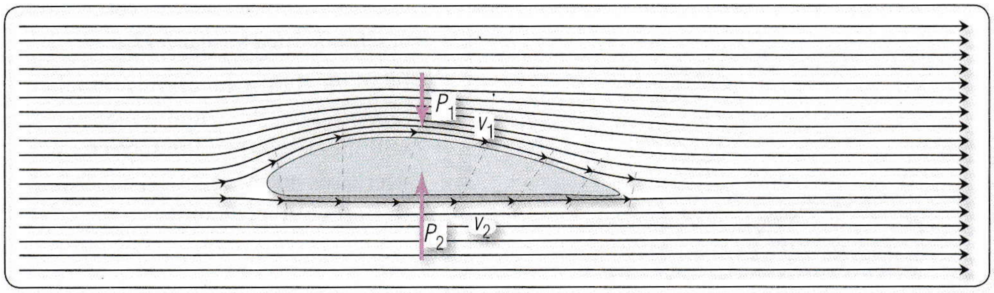
As expected, fluid pressure decreases with an increase of speed.



17-25 Pipe constrictions often occur in real plumbing systems.

17.18 Lift

Flowing fluids can generate dynamic forces on the surfaces they contact and on objects immersed within them. The Creator's design of fish and birds, which move easily through fluids, utilizes this principle. Long ago, humans discovered the ability of wind to generate useful forces, like those utilized by windmills and sailing ships. More recently, in attempts to emulate bird flight, people produced contraptions that create a lifting force. Any device that generates **lift** as air flows along its surface is an **airfoil**. Airfoils are typically long, narrow, and flattened solid objects that are streamlined, having a teardrop-shaped cross section. An airplane wing is one kind of artificial airfoil. Similar objects that create lift in liquid are **hydrofoils**.



17-26 Streamlines over an airfoil illustrate the theory of the Bernoulli principle of lift.

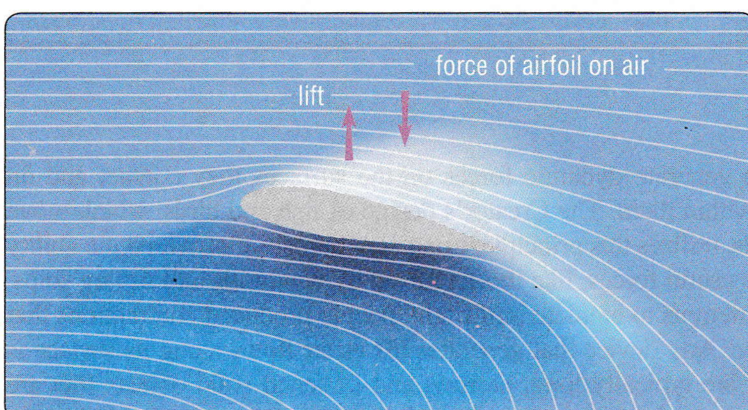
Lift can be modeled extremely well by modern supercomputers, but there are various theories that describe what actually causes lift. The Bernoulli principle is commonly taught as the cause of lift, suggesting that a plane wing moving through air splits the air in front of it. According to this theory, the principle of flow continuity demands that the air that flows above the wing must meet up at the wing's trailing edge with the air that flows under it. If the wing's upper surface is more curved than its lower surface, the air on top will move faster, so its pressure will be lower than that on the underside of the wing. This pressure difference causes a net lifting force, as predicted by the Bernoulli principle. See Figure 17-26.

But there are several problems with this approach. First, nothing actually requires the two paths of air to reunite at the wing's trailing edge. In fact, when observed, the two flows usually do *not* reunite. Second, a wing with a steeply curved upper surface would not work upside down. High performance aircraft have wings with symmetrical cross sections, yet they still manage to generate lift. Third, airfoils divert great masses of air in the opposite direction to the direction of the lifting force (see Figure 17-28), but this is not predicted by the Bernoulli principle. Fourth, objects that present only a single surface to flowing air experience significant lift without a corresponding flow adjacent to the opposite surface (e.g., a sheet of plywood lifted off the ground on a gusty day).

Henri Marie Coandă (1886–1972) was a Romanian aeronautical engineer, aircraft designer, and inventor. He was instrumental in early aerodynamics research and built a rudimentary jet engine in 1910.

A better explanation of lift involves the Coandă effect and Newton's third law. The **Coandă effect** states that fluids moving by a gently curved surface tend to follow the curvature of the surface due to forces of adhesion and *fluid viscosity*. Fluid molecules immediately next to a moving surface adhere to it and are thus motionless. Molecules slightly farther away move slowly relative to the surface, and those at a greater distance move rapidly. These position-dependent movements compose the *boundary layer effect*. Thus, a surface, such as a wing, that moves through fluid drags that fluid along in a path similar to the surface's curvature.

Because an aircraft wing generating lift is tilted upward slightly, it compresses the air below it, causing some of the air in front of the wing to rise up and flow over it. The Coandă effect causes this air to follow the wing's surface, with air molecules spreading out above the wing due to inertia and low air viscosity. This spreading reduces the density of the air and thus the air pressure above the wing. Air even farther above the wing then rushes in to fill this low-pressure region.



17-27 Streamlines showing the Coandă effect. The diagram exaggerates the shape of the streamlines to illustrate the effect.

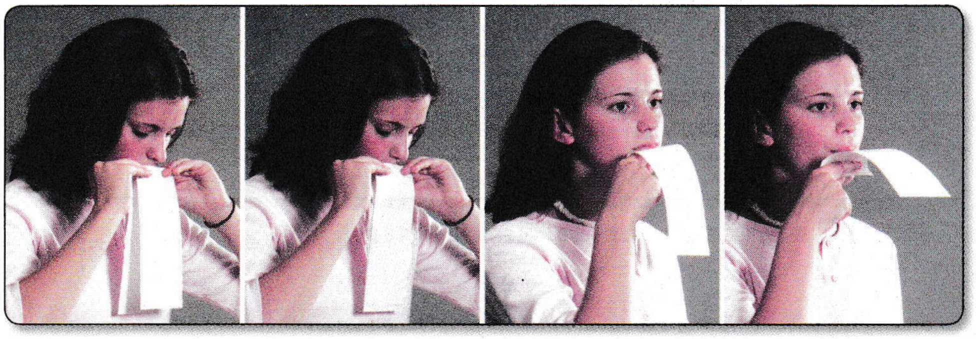
The Coandă effect thus accelerates the air *above* the wing *downward* toward the top of the wing. According to Newton's third law, the surrounding air, in reaction to the force the wing exerts on the air, must exert an opposite upward force on the wing, which is lift. Notice that most of the lifting force is generated above the wing rather than below it. The downward moving air then spills behind the moving wing, as seen in the adjacent figure.

Unlike the Bernoulli principle, the Coandă effect accounts for the upside-down flight of aerobatic and military aircraft, as well as the functioning of wings streamlined on both surfaces. It also better explains why sails, propellers, and fluid switches work. Many physicists suggest that aerodynamic lift is actually a combination of the Coandă effect, the Bernoulli principle, and other complex physical principles of fluid mechanics.

You can verify the Coandă effect by a simple experiment. Hold two sheets of paper about an inch apart, as in Figure 17-30. Blow steadily between the sheets. You might expect them to fly out from the force of your blowing, but instead they draw together. The moving air between them exerts less pressure on them than the still air around them, so they are pushed together. The two photographs on the right in Figure 17-30 demonstrate how lift is created by the Coandă effect.

17-28 As predicted by the Coandă model of lift, this aircraft diverts huge amounts of air downward as it creates lift.

17-29 Helicopters generate lift using a combination of Bernoulli's principle, the Coandă effect, and Newton's laws of motion.



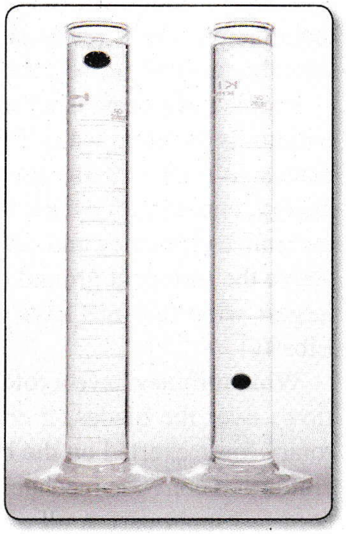
17-30 These two demonstrations show how unbalanced forces across a fluid boundary created by the Coandă effect can produce work.

17.19 Real Fluids

In real-world aerodynamics and hydrodynamics, designers and engineers must take into account friction, fluid viscosity, and turbulence, all of which greatly complicate the analysis of fluid flow around immersed objects.

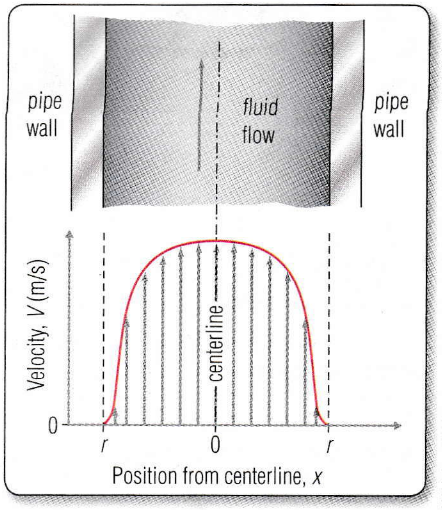
The cohesive forces between particles of a fluid produce a type of internal friction called **viscosity**. Viscosity determines how freely a fluid flows. The coefficient of viscosity (η) indicates the resistance of a fluid to flow. Lower viscosity coefficients mean that the fluids flow more easily than those with higher viscosity coefficients. For instance, water has a lower viscosity than molasses. Viscosity is familiarly known as the "thickness" of a fluid.

The adhesive forces between a flowing fluid and its confining walls (such as a pipe) cause the outermost particles of fluid to be essentially stationary. Particles farther into the fluid have small velocities that increase with distance from the wall of the pipe.



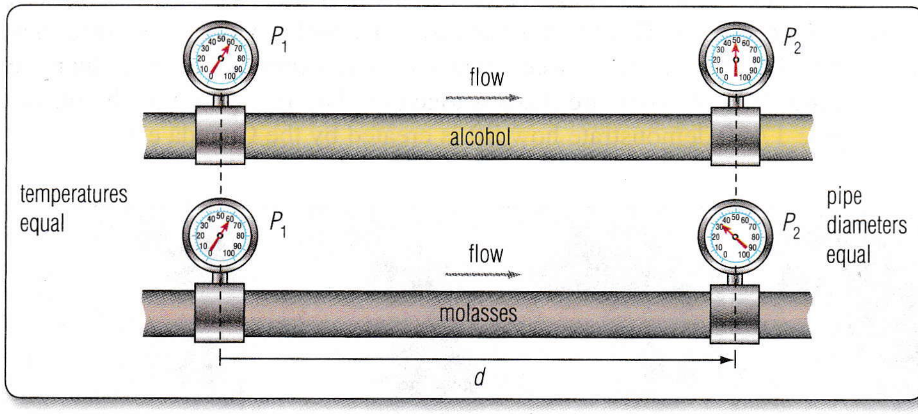
17-31 Viscosity determines the ease with which objects move through a fluid. Both marbles were dropped at the same instant. The left liquid is a thick syrup; the right liquid is water.

The coefficient of viscosity (η) is given the SI unit of pascal-second (Pa·s). An older unit of viscosity is the poise. Viscosity coefficients are tabulated at a specified temperature, since temperature significantly affects cohesive forces.



17-32 Viscosity and friction with the wall surface reduce fluid velocity near the margins of a pipe.

The fluid particles at the center have the highest velocities. The farther a particle is from the wall of the pipe, the faster it goes. Therefore, the flow of fluid at the center of a large pipe is faster than the fluid at the center of a smaller pipe at the same supply pressure. This effect is a combination of friction with the pipe and fluid viscosity. According to the principles of energy conservation, the conversion of the mechanical energy of fluid particles to thermal energy (internal energy) through friction and viscous flow results in a decrease in fluid pressure and kinetic energy (flow velocity) along the length of a pipe. This is why the shower in a one-story house farthest from the water supply pipe has the slowest flow (least pressure).



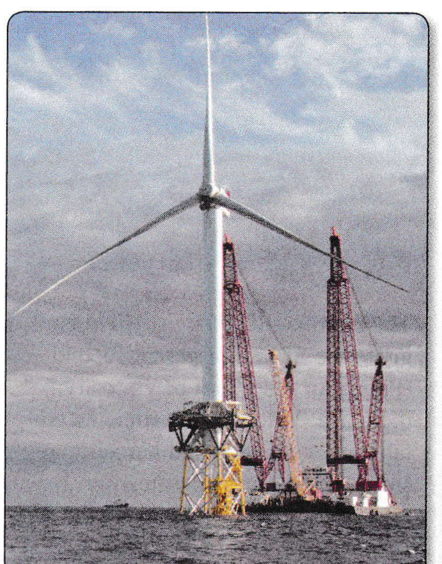
17-33 Viscosity lowers pressure with distance as a fluid moves through a pipe.

17.20 Using Fluid Mechanics to Solve Problems

Factors that drive the investigation of new electrical energy sources are cost, accessibility, safety, impact on the environment, and renewability. One emerging technology, which really isn't all that new, is wind power generation. How can wind be most effectively used to generate electricity?

People have been using wind power for centuries. For example, the Dutch used windmills to pump water from their low-lying lands, and many countries lacking extensive river systems used wind to grind grain. In an attempt to harness wind energy, engineers have used computers to develop aerodynamic *wind turbines*. To maximize efficiency and reduce structural stresses, wind turbines are elevated well above the turbulent ground breezes to expose their blades to smoother winds. The largest wind turbines have a hub height nearly three times that of the Statue of Liberty!

Wind turbines have a rotor that mounts two or three long, narrow blades. As air flows over the blades, it creates lift similar to that on an airplane's wings. The rotary force exerted on the blades spins the turbine, which turns an electrical generator that converts mechanical energy to electrical energy. Wind turbines may be used to supply part or all of the electrical needs of a single dwelling, or they may provide large-scale power generation, which requires hundreds of wind turbines in facilities called *wind farms*.



17-34 The world's largest wind turbines are capable of generating 5 MW of electrical power.

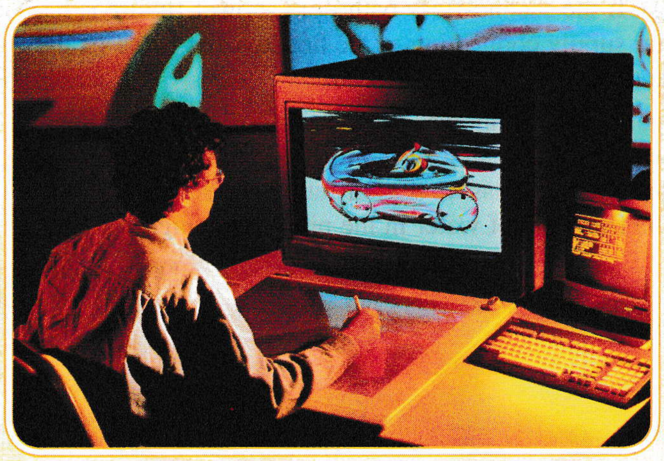
To have the greatest economical benefit, wind turbines need to be efficient. However, the maximum theoretical efficiency for flow machines such as wind turbines is only about 59%. That is, 59% of the kinetic energy available in the wind is converted into mechanical energy. Even more loss occurs as mechanical energy is converted to electrical energy. Advanced technology wind turbine installations can achieve efficiencies of 40–50%. The Department of Energy estimates that the United States could potentially supply up to 20% of its energy needs with wind power by the year 2030. This would provide electricity at only a fraction of the cost of coal, gas, and nuclear energy without the accompanying environmental and public hazards. However, many political and economic challenges must be solved before this goal can be reached.

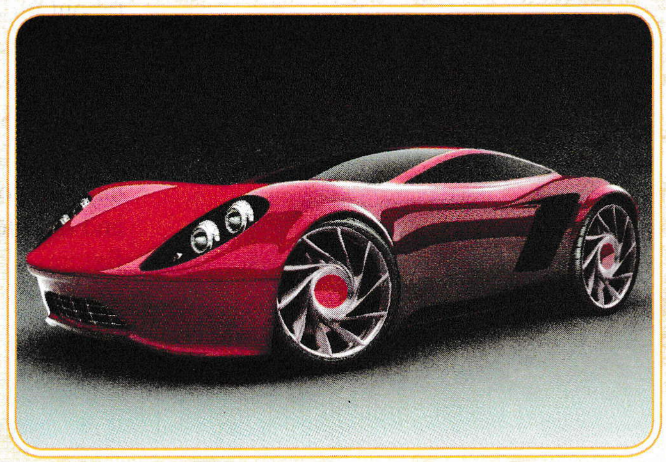
Decisions, Decisions

In spite of wind power's apparent economical benefits, many people oppose wind farms because of the noise, visual clutter, and effects on bird populations. What may people presuppose when making decisions about the benefits and liabilities of wind power?

FACETS of PHYSICS

Aerodynamically Designed Cars





In order to conserve energy and reduce emissions, automobile designers are doing their best to make cars more fuel-efficient. Although increasing engine efficiency and making cars lighter are important, much of the fuel savings comes from designing the body to move smoothly through the air.

Actually, the idea of an aerodynamically efficient car is not entirely new. As early as 1934, Chrysler produced the Airflow, a sleek vehicle with smooth, rounded curves and fenders. The idea did not become popular, however, until the fuel shortage crises of the 1970s forced manufacturers and consumers to explore every avenue of cutting fuel consumption.

At highway speeds, a car uses more than half its power to overcome air resistance. Therefore, reducing air resistance reduces fuel consumption. The main goal is to make the flow of air around the car as nearly laminar as possible. Models of new designs are first tested using sophisticated computer modeling. Fractional-scale and full-scale testing is done in wind tunnels, where smoke streams around the models, revealing turbulence and potential drag.

If you compare newer passenger cars (including SUVs and energy hybrids) with older models, you will see that the latest are designed to let air flow smoothly over, under, and around them. Headlights are molded into the fenders, front hood lines flow smoothly into the front bumper structure, windows are flush with the body, and the overall profile promotes the laminar flow of air over the vehicle. Even the underside of the car is engineered to remove as many obstructions to the flow of air as possible. Most recreational and crossover vehicles, despite their boxy profiles, are designed to minimize wind resistance.

These efforts, combined with more efficient engines, hybrid designs, and fuel cell-powered electric motors, have dramatically improved the fuel efficiency of passenger vehicles.