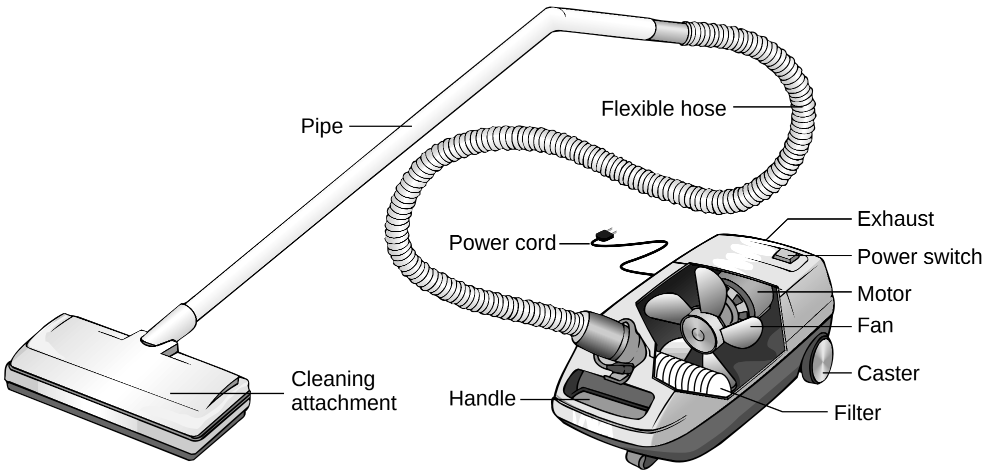

Section 5.4

Vacuum Cleaners

When we examined garden watering in Section 5.1, we examined tools that permit a fluid to flow out of a hose. In this section, we'll look at the reverse, a device that draws a fluid into a hose. That device is a vacuum cleaner, and the fluid that it draws inward is air. This moving air gathers dust and debris as it rushes into the vacuum cleaner, which is why vacuum cleaners are useful.

Questions to Think About: *Why does nature "abhor a vacuum"? If you remove some of the air from a region of space, how does the surrounding air respond? How does wind push on the objects it passes? Can you think of cases in which moving air actually picks up at least some of the objects it passes? How does the vacuum cleaner create the partial vacuum it uses to draw air into the hose? Why does the vacuum cleaner require electric power?*

Experiments to Do: *Find a vacuum cleaner with a hose and watch how the airflow draws in dust. As you shrink the diameter of the cleaning attachment or partially block the end of the hose, does the air entering the hose move faster or slower? Is a partially blocked hose more or less effective at trapping dust than an unblocked one? Try to vacuum up tiny objects and then larger ones; which are easier? Block the airflow into the hose completely and notice what happens to the motor's pitch. Why should the motor's rotation depend on the airflow?*

Even without a vacuum cleaner, you can try similar experiments with a drinking straw or a cardboard tube. You could pretend to be a vacuum cleaner by sucking dust into your mouth, but you'd do better to blow it around instead. Try blowing on different-sized objects with different-sized openings on the straw or tube. Is a narrow or a wide opening most effective? Which blow about more easily: small objects or large objects?

Air Flowing into the Vacuum Cleaner

Vacuum cleaners use swiftly moving air to sweep up dust. In this section, we'll examine how they create that swiftly moving air and why dust is so easily carried along by it. But let's forget dust for the moment and look at how air itself flows into a vacuum cleaner. In particular, let's try to understand the airflow in a canister vacuum cleaner with a long hose.

For simplicity, we'll reduce the machine to a hose and a fan (Fig. 5.4.1). The fan draws air through the hose. Outside the hose, the air is stationary at atmospheric pressure. When you turn the fan on, the pressure inside the hose drops and a partial vacuum is created (hence the name "vacuum cleaner"). Since air accelerates from high pressure to low pressure ("nature abhors a vacuum"), outside air rushes into the hose. Once steady-state flow is reached, a process that takes a second or two, the pressures and velocities of the air in the hose become steady, too. However, these pressures and velocities are different at different points along the hose. We can understand these differences using Bernoulli's equation.

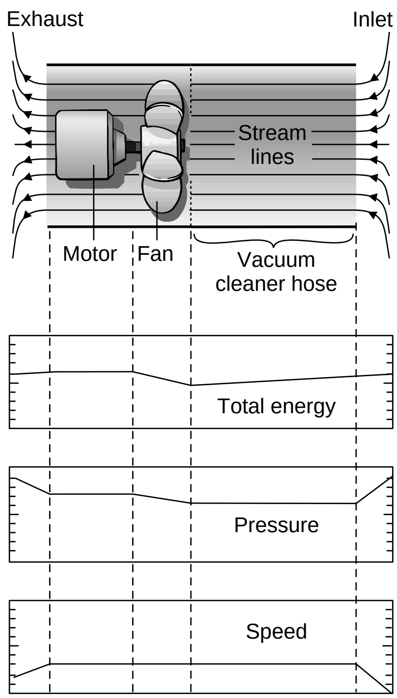

Fig. 5.4.1 - As air flows into the inlet of a vacuum cleaner hose, its pressure drops and its speed increases. The fan boosts the air's total energy, helping it overcome viscous losses of total energy so that it can return to the outside air through the outlet.

Strictly speaking, we shouldn't be using Bernoulli's equation; it applies only to incompressible fluids in perfect steady-state flow, and air certainly isn't incompressible. But if certain conditions are met—if the air's velocity is less than about 300 km / h, and if there are no pressure differences of more than one tenth of an atmosphere—then we can *consider* air to be incompressible, since its density will remain fairly constant. That makes things much easier for us here, just as it did when we discussed curve balls and airplanes. We can also ignore gravity. If the air were flowing up and down hundreds of meters, we would need to include it; but here it's inconsequential, since the whole vacuum cleaner is at one altitude.

With air behaving as an incompressible fluid and gravity out of the picture, Bernoulli's equation predicts a simple result. The sum of the air's pressure potential energy and kinetic energy should be constant along a streamline. Thus, if a portion of air speeds up as it moves along its streamline, its pressure must drop; if it slows down, its pressure must rise.

The pressure inside the vacuum cleaner hose is low, so air accelerates toward the inlet (Fig. 5.4.1) and its speed increases as its pressure drops. Inside the hose, the air has the same total energy that it had before it entered, but some of its pressure potential energy has been converted to kinetic energy.

Even though it doesn't look like one, the inlet to the hose behaves as a nozzle. Air in front of the inlet bends first toward the inlet and then straightens out to pass directly into the hose. These two bends are identical to those experienced by a fluid as it passes through a fully formed nozzle (Fig. 5.1.3) and similar pressure changes occur. As it enters the hose end, the air's pressure drops and its speed increases. It has exchanged pressure potential energy for kinetic energy.

We can see these speed and pressure effects by looking at the spacing of the streamlines. In Fig. 5.4.1, the streamlines bunch together as they enter the inlet. All of the air is being squeezed through a narrow channel. The closely spaced streamlines indicate fast moving air and since this air has exchanged pressure potential energy for kinetic energy, its pressure must now be relatively low.

Once inside the hose, the air continues at high speed and low pressure until it encounters the fan. The fan increases the air's total energy, using a technique we will look at later. Because the fan's inlet and outlet have the same diameter, the air's speed doesn't change as it moves through the fan; instead, its pressure and pressure potential energy increase. Low-pressure air enters the fan through the hose and higher-pressure air leaves the fan through the exhaust port. Thus the fan maintains a pressure imbalance inside the vacuum cleaner. The low pressure inside the hose is what got the air moving in the first place!

While the air leaving the fan may still be below atmospheric pressure, it is now traveling fast so that much of its total energy is in the form of kinetic energy. As this air flows out of the exhaust port, its streamlines spread out (Fig. 5.4.1). This spreading indicates that the air is slowing down and exchanging kinetic energy for pressure potential energy. The air's pressure rises to atmospheric pressure and it reenters the room. The air has completed its trip through the vacuum cleaner.

But when you add a narrow cleaning attachment to the hose (Fig. 5.4.2), the airflow becomes more complicated. For the air to continue flowing through the fan at the same rate as before, it must rush rapidly through the narrow channel of the attachment. The streamlines bunch tightly together, indicating a dramatic rise in speed and severe drop in pressure.

The dramatic increase in speed and drop in pressure that occur when a steady flow of fluid passes through a narrow channel is called the **Venturi effect**, after its discoverer, Italian physicist G. B. Venturi (1746–1822). The Venturi effect is a special case of the **Bernoulli effect**, which recognizes that any increase in a fluid's velocity along a streamline is accompanied by a drop in pressure.

While the Bernoulli effect has many important applications in the world around us, it doesn't apply to every situation. You should remember that the Bernoulli effect only occurs *along a streamline*, in fluid that is in *steady-state flow*. Just because air is moving quickly doesn't mean that its pressure is low. The air in the cabin of a passing aircraft is really hustling along, relative to the earth, but its pressure is essentially atmospheric.

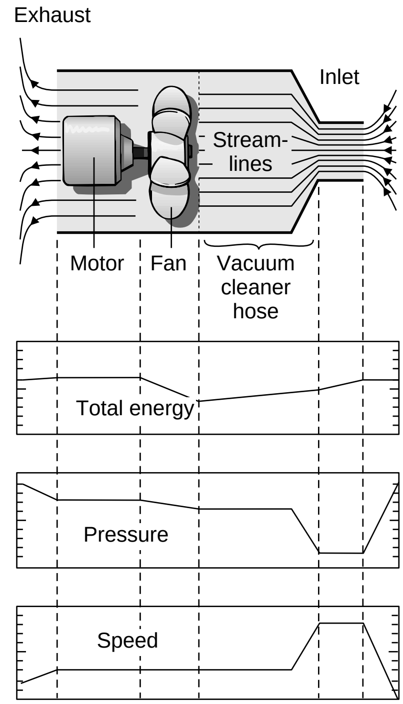

Fig. 5.4.2 - When you add a narrow cleaning attachment to the end of the vacuum cleaner hose, the air in the inlet reaches very high speed and relatively low pressure. The attachment's narrow channel is short to minimize the loss of total energy to viscous forces.

CHECK YOUR UNDERSTANDING #1: Spray Painting

In many paint and garden sprayers, air or water passes through a narrow channel on its way out of the nozzle. A thin tube joins the narrow channel at right angles and atmospheric pressure pushes paint or garden chemicals through that tube and into the channel. Evidently, the pressure inside the channel is less than atmospheric pressure. How can this be possible?

Dust and Drag Forces

Now that we understand speed and pressure in a vacuum cleaner, let's return to the dust. As air rushes toward the opening in the cleaning attachment, it carries dust with it. This phenomenon, in which a particle or portion of fluid is carried along in the flow of another fluid, is called **entrainment**. Dust entrainment is most effective in very high-speed air, which is why a narrow attachment cleans a carpet more thoroughly than a wide one.

Dust particles are entrained in air by drag forces. Whether the dust moves through the air or the air moves past the dust, these friction-like forces act to bring the dust to rest relative to the air. The drag force that's most important in vacuum cleaning is viscous drag. Viscous drag is what slows laminar water flow through a pipe. The pipe is held in place and can't move, so viscous drag slows the water down. But when air flows past a dust particle, the dust particle moves easily and viscous drag carries it along in the air.

The amount of viscous drag force that the air exerts on a dust particle is proportional to the diameter of the particle and to the difference in velocities between the particle and the air. This relationship comes about because the amount of air the particle encounters via viscosity is proportional to its girth and to its velocity through the air. As always, the viscous drag force on the particle is directed so that it brings the particle to the same velocity as the air. Of course, the particle pushes back on the air with an equal but oppositely directed drag force.

Because dust particles are often just tiny rocks, we might expect viscous drag to affect rocks and dust particles equally. But that isn't so. At issue is how large the drag force is when compared to an object's weight and mass. A dust particle experiences less viscous drag than a rock because of their different diameters. While drag is proportional to diameter, the dust particle is much lighter and less massive than the rock—and mass and weight are proportional to diameter to the *third power*. Think of how many dust particles you can make by grinding up even a small rock, and consider how light each of those dust particles must be. With so little weight to hold them in place, it's not surprising that viscous drag forces easily blow about dust particles.

Dust particles are so incredibly light that they are easily borne aloft by air currents. Dust swept into the air by winds, emitted by industrial smokestacks, or blown upward in volcanic eruptions can remain in the atmosphere for days, weeks, or even years. Thus volcanic ash from the 1980 explosion of Mount St. Helens in Washington State was carried through the Midwest and even to the eastern United States.

Although dust tries to fall, viscous drag keeps it from descending rapidly. Like any object falling through the atmosphere, dust has a terminal velocity, the velocity at which the upward viscous drag force on it exactly cancels its downward weight. A falling object accelerates downward only up to its terminal velocity, at which point the net force on it is zero and it descends at constant velocity. While a person's terminal velocity may be 300 km/h without a parachute and 30 km/h with a parachute, a dust particle's terminal velocity may be only 0.0036 km/h (1 mm per second). Any upward air current will therefore lift it back into the sky. In a calm, sunlit room, you can often see dust particles drifting about with the air currents, prevented from falling by the viscous drag force.

This same viscous drag force is what lets air carry dust particles into the vacuum cleaner. The force reduces any difference in velocities between the air and the dust, so if the air rushes into the vacuum cleaner, the dust will, too. The faster the air moves, the larger the viscous drag force on a particle. This increase in force with air speed explains why a narrow attachment cleans better than the hose alone: the air speed is higher near the attachment and the drag force is larger.

Unfortunately, viscous drag also slows the air as it passes close to carpet fibers or the surface of the floor. It's hard to keep air moving quickly near those surfaces. Removing really ground-in dirt from a carpet or floor requires a powerful fan and the high air speed that comes from making air pass through a narrow opening. The need for high air speed also explains why battery-powered or poor-quality vacuum cleaners don't clean well: their fans are too weak to move the air fast enough to remove the dirt effectively, particularly near surfaces. Beater brushes, which jostle the dirt away from surfaces, help to move the dirt into the fast-moving air stream so that it can be carried into the vacuum cleaner.

All this explains why vacuum cleaners can pick up small particles; but why should they have trouble collecting large objects? First, the viscous drag force on a marble is just not large enough to overcome its weight and lift it up into the vacuum cleaner; you'd probably have to sweep over it a couple of times unsuccessfully and then pick it up with your hand and drop it into the hose. Second, a marble is much larger than a dust particle, and a much larger Reynolds number characterizes the flow of air around it. Viscous drag is the dominant drag force only when the flow is laminar. When vacuuming, the flow of air around a dust particle is laminar, but the flow of air around a marble includes turbulence. As a result, the marble experiences pressure drag forces. However, even pressure drag forces aren't able to carry the marble into the vacuum cleaner.

CHECK YOUR UNDERSTANDING #2: Keeping Clouds in the Sky
Clouds consist of countless tiny water droplets. Water is more dense than air, so why don't these water droplets fall?

The Fan

We've looked at how a vacuum cleaner picks up dust; now it's time to look at the fan. Without the fan, viscous drag forces would quickly stop air from flowing through the cleaning hose by converting its total energy into thermal energy. This effect is most severe when you use a narrow cleaning attachment, because the high-speed air inside that attachment loses total energy particularly quickly.

To keep air moving through the hose, the fan pumps the air from the low-pressure region in the cleaning hose to the high-pressure region at the exhaust port, against its natural direction of flow. The fan does work on the air and replaces the energy that viscous drag has converted to thermal energy. Because the fan increases the air's total energy, the airflow through the fan is *not steady-state flow*; the air's pressure increases as it flows through the fan without a corresponding decrease in speed.

In its basic form, the fan is just a rotating array of ramp-like blades that push the air as they turn past (Fig. 5.4.3). These blades do work on the air, using energy provided by an electric motor, which of course gets its energy from the electric power company. What is interesting here is that work is being done by a rotational motion, not the translational motion that we normally associate with work. We have seen that work is done by exerting a force while traveling a distance in the direction of that force. But work can also be done by exerting a torque while rotating through an angle in the direction of that torque.

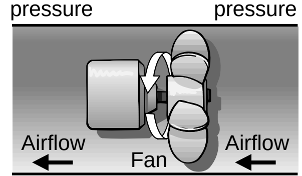

Fig. 5.4.3 - As a vacuum cleaner's fan rotates, its blades transfer air from the low-pressure side to the high-pressure side, doing work on the air in the process.

To see how you can do work with torques, think of a basketball. If you exert a torque on this basketball, it begins to rotate; you've done work on it and given it rotational kinetic energy. If you now exert a torque on it in the other direction, so that the torque and the direction of rotation are opposite one another, you do negative work on the basketball and it comes to rest.

The amount of work that you do in this manner is equal to the product of the torque you exert times the angle through which the object rotates. This relationship can be written as a word equation:

$$\text{work} = \text{torque} \cdot \text{angle of rotation}, \tag{5.4.1}$$

in symbols:

$$W = \boldsymbol{\tau} \cdot \boldsymbol{\theta},$$

and in everyday language:

If you're not twisting it or it's not turning, then you're not working.

In this relationship, the angle of rotation is in the direction of the torque. If the object turns in the direction opposite your torque, it does work on you! To actually calculate the work you do on something when you twist it, you must measure the angle of rotation in the natural units of angle: radians. 1 radian is equal to $180/\pi$ degrees (about 57.3°). While degrees are probably more familiar to you than radians, using degrees in Eq. 5.4.1 will lead to incorrect results.

Eq. 5.4.1 is useful in devices such as bicycles and electric motors, where energy is transferred via rotational motion. At present, however, you only need to recognize that the motor does work on the fan via a torque and that the fan uses this work to pump air from low pressure to high pressure.

This concept helps explain the high-pitched whine that most vacuum cleaners emit when you block the airflow through their hoses. If no air can reach the low-pressure side of the fan, the fan can't pump any air to the high-pressure side. Since the fan moves no air, it does no work and spins idly. The motor is still turning the fan, but neither one is doing any work; the motor isn't exerting any torque on the fan, and the fan is turning freely. Since the fan offers no resistance to rotation, the motor and the fan turn faster and faster, so that the motor quickly exceeds its rated rotational speed and begins to whine. When you unblock the airflow, the fan and motor begin to do work on the air, the motor slows down, and the whine disappears.

CHECK YOUR UNDERSTANDING #3: Moving the Air

In terms of fluid flow, how does a household fan cause air to move?

CHECK YOUR FIGURES #1: Doing Work on Your Bicycle

You are using a wrench to tighten a bolt. To keep the bolt turning steadily, you must exert a torque of 10 N·m on it. By the time you have completed one full turn (360° or 2π radians), how much work have you done?

Filtering the Dust

A vacuum cleaner uses a fan to create a moving stream of air; this air entrains dust particles by way of viscous drag forces. But the vacuum cleaner doesn't make the air vanish; it returns the air to the room once that air has passed through the fan. What keeps the dust from returning to the room, too?

The answer, of course, is a filter, a device that blocks the dust particles while permitting air molecules to pass (Fig. 5.4.4). A typical filter is made of porous paper or cloth, with fibers that are loosely woven to create openings or pores large enough for air to pass, but too small for dust to pass.

This simple filtration is complicated by viscous drag. The air that passes through the filter's pores loses some of its total energy trying to move past the stationary air at the surfaces of the pores. Just as the viscous drag force on a particle becomes larger as the particle's speed through the air increases, so the viscous drag force on the air becomes larger as the air's speed through a pore increases. The faster air moves through a pore, the more energy it loses during the trip. To minimize the energy lost to viscous drag, the vacuum cleaner must move the air slowly through the filter. It does this by using a very large filter so that the air has lots of surface area and many pores through which to flow.

When the filter is new, the air flows slowly through its pores and loses relatively little energy; the filter removes dust from the air without much effect on the air itself, and the vacuum cleaner works well. But as dust begins to plug the pores in the filter, the air must move more and more quickly through the pores that remain open. The air loses much of its energy as it struggles to pass through the filter. The filter thus slows the flow of air, and the vacuum cleaner doesn't clean well anymore.

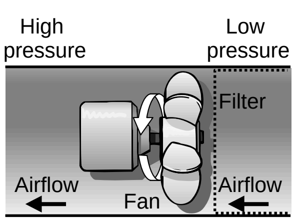

Fig. 5.4.4 - In a canister vacuum cleaner, air flowing through the hose first passes through the filter and then through the fan. The fan pumps air from the low-pressure region inside the vacuum cleaner to the atmospheric pressure outside.

CHECK YOUR UNDERSTANDING #4: The Beekeeper's Bind

Honey flows very slowly out of the honeycomb or through a cheesecloth filter. What slows it down?

Practical Vacuum Cleaners

Vacuum cleaners come in two main types: those with the filter before the fan and those with the filter after the fan. The first type includes canister vacuum cleaners, which send air rushing down the hose so that it first passes through the filter and then through the fan (Fig. 5.4.4). The fan's job is to pump low-pressure air from the filter to the high-pressure side so that it can flow out into the room. The low-pressure air inside the vacuum cleaner is well below atmospheric pressure and would not naturally flow through the filter and into the room. The fan increases the air's pressure so that it can complete its trip and return to the room.

In contrast, upright vacuum cleaners place the filter after the fan, so that air flowing up from the carpet first passes through the fan, then past the motor, and then through the filter (Fig. 5.4.5). Perhaps the biggest difference between the canister and upright vacuum cleaners is in what happens when you vacuum up an object like a penny. In the canister vacuum, the penny stops in the filter and never gets into the fan; in the upright vacuum, the penny flies right through the fan. Since a penny is fairly heavy and the vacuum cleaner has trouble moving it with drag in the first place, the penny tends to rattle around in the fan, making a terrific racket.

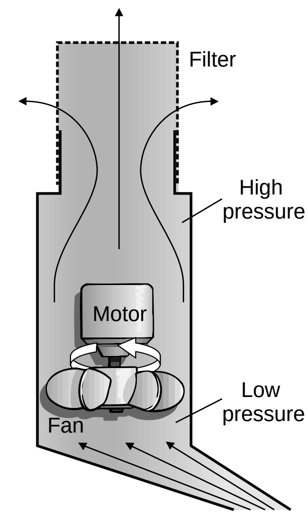

Fig. 5.4.5 - In an upright vacuum cleaner, air flowing up from the carpet is pumped by the fan and flows out into the room through the filter.

CHECK YOUR UNDERSTANDING #5: When to Use a Mop
Why is it dangerous to vacuum up water with an upright vacuum cleaner?