CHAPTER 1

The Piston Engine

Most cars, airplanes, and chainsaws get their power from burning hydrocarbons in a combustion chamber. We say they have *internal combustion engines*. There are many types of internal combustion engines: jet engines, rotary engines, diesel engines, and more. In this chapter, we are going to explain how one type, piston engines, work. Most cars have piston engines.

Most piston engines burn gasoline, which is a blend of liquid hydrocarbons. Hydrocarbons are molecules made of hydrogen and carbon (and maybe a little oxygen). In the presence of oxygen and heat, hydrocarbons burn — the carbon combines with oxygen to become CO_2, and the hydrogen combines with oxygen to become H_2O. In the process, heat is released, which causes the gases in the cylinder to create a lot of pressure on the piston.

1.1   Parts of the Engine

The engine block is a big hunk of metal. There are cylindrical holes bored into the engine block. A piston can slide up and down the cylinder. There are two valves in the wall of the cylinder:

- Before the burn, one valve opens to let ethanol and air into the cylinder.

- After the burn, the other valve opens to let the exhaust out.

There is also a spark plug, which creates the spark that triggers the burn.

As you give the engine more gas, the cylinder does more frequent burns. When the engine is just idling, the cylinder fires about 9 times per second. When you depress the gas pedal all the way down, it is more like 40 times per second.

The cylinder has a rod that connects it to the crank shaft. As the pistons move back and forth, the crank shaft turns around and around. Sometimes a piston is pushing the crankshaft, and sometimes the crank shaft is pushing or pulling the piston. All the cylinders share one crank shaft.

How many cylinders does a car have? Nearly all car models have between 3 and 8 cylinders. The opening of the valve and the firing of the spark plugs are timed so that cylinders all do their burns at different times. This makes the total power delivered to the crank
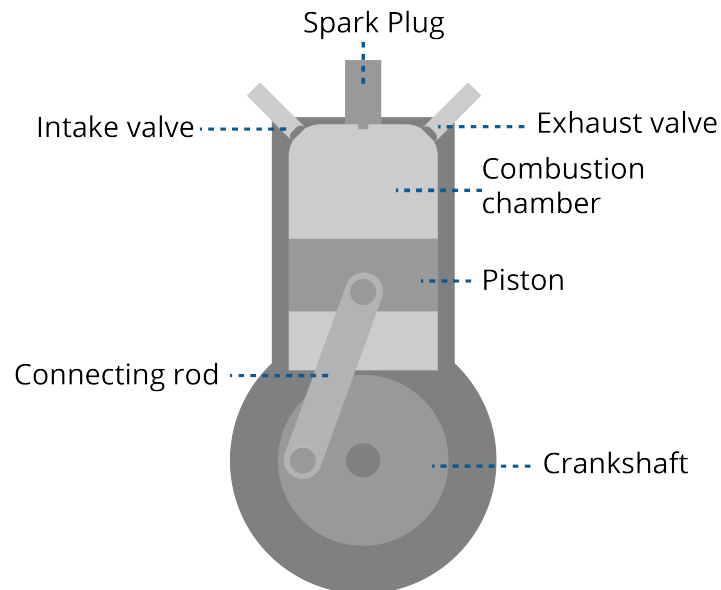
shaft smoother.

Figure 1.1: A cross-section of an 8 cylinder engine.

1.2   The Four-Stroke Process

Cars have four-stroke engines — this means for every two rotations of the crank shaft, each cylinder fires once. Smaller engines, like those in chainsaws, are often two-stroke engines — every cylinder fires every time the crank shaft rotates. For now, let's focus on four-stroke engines.

Here is the cycle of a single cylinder:

- As the drive shaft turns, it pulls the piston down. The intake valve opens and lets the gas/air mixture into the combustion chamber. See Figure 1.2.

- As the piston reaches the bottom of the stroke, the intake valve closes.

- Now, the crank shaft starts to push the piston up, compressing the gas and oxygen. See Figure 1.3.

- As the piston reaches the top of its stroke, the spark plug creates a spark. The fuel and oxygen burn quickly. The cool liquid fuel becomes hot carbon dioxide and water vapor.

- There is now very high pressure inside the cylinder. It pushes hard on the piston, which pushes the crank shaft.
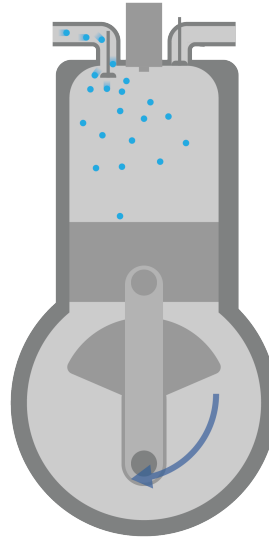
Intake

Figure 1.2: The intake stroke allows gas and oxygen into the combustion chamber.
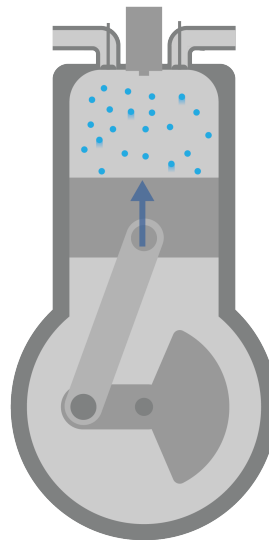
Compression

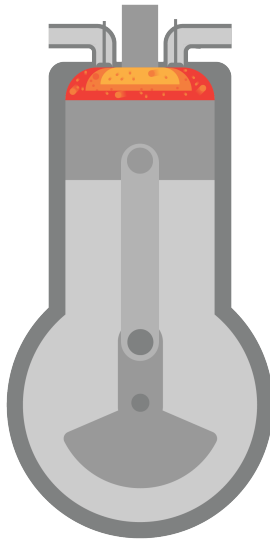Figure 1.3: The compression stroke compresses the gas and oxygen.

Combustion

Figure 1.4: On the combustion stroke, the gas and oxygen merge into a hot ignited fuel.

- When the piston reaches the bottom of this stroke, the exhaust valve opens.

- As the crank shaft pushes the piston up, the carbon dioxide and water vapor is pushed out.

- When the piston reaches the top of this stroke, the exhaust valve is closed.

1.3   Dealing with Heat

Burning fuel inside a block of metal generates a large amount of heat. If there is too much heat, parts of the engine will start to melt. So, modern car engines are liquid cooled — there are arteries in the engine block carrying a liquid (called "coolant"). The hot coolant is pumped through the radiator (where the air passing through takes away the heat), then back into the engine.

Note that the heat that is carried away by the coolant is wasted energy. In fact, of the total energy created in burning the fuel, most car engines only transfer about 30% to turning the crank shaft. About 35% of the heat goes out with the exhaust. About 30% is carried away by the coolant. The remaining waste (usually about 5%) is lost to friction.
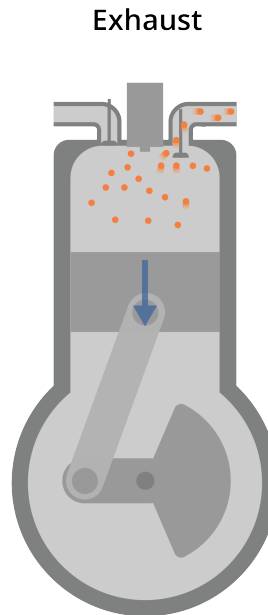
Exhaust

Figure 1.5: On the exhaust stroke, the burnt gases are expelled from the cylinder.

1.4   Dealing with Friction

From the description, it is clear that there is a great deal of metal sliding against metal, which would grind the engine up quickly if there were no lubrication. In a modern car, the moving parts in the engine are constantly bathed in oil. There is an oil pump that causes it to get sprayed on the crankshaft, the connecting rod, and in the cylinder under the piston (that is, not on the combustion side).

The oil eventually falls through the oil into a pan at the bottom of the engine. The oil pump sucks the oil up, pushes it through a filter (so bits of metal are not pumped back into the engine), and is then sprayed on the moving parts again.

1.5   Challenges

With a piston engine, there are a lot of things that can go wrong. Let's enumerate a few:

- *The seal around the piston leaks*. Mechanics say "We aren't getting any compression." The cylinder doesn't get much power to the drive train.

- *The valves open or the spark plug fires at the wrong time.* This is known as a timing problem.

- *The spark plug doesn't make a spark.* The spark plug has two prongs of metal and electrons jump from one to the other. For a good spark, the prongs need to be a very precise distance apart. Sometimes you need to bend one of the prongs to get the right gap. This is known as *gapping*.

- *The mix of fuel and oxygen is wrong.* If there is too much fuel and not enough oxygen (so not all the fuel burns), we say the mix is too rich. If there is not enough fuel (so the pressure created by the burn is as high as possible), we say the mix is too lean.

1.6   How We Measure Engines

If you look up the specs on an engine, you will see the following:

- The number of cylinders

- The cylinder bore, which is the diameter of the cylinder

- The piston stroke, which is the distance the piston travels in the cylinder

- The compression ratio, which is the ratio between the maximum volume of the combustion change and the minimum volume of the combustion chamber

- What fuel it runs on

The difference between the minimum and maximum value of the cylinder is known as its *displacement*. The displacement represents the volume of air/fuel sucked into the intake valve before the compression begins.

We often talk about the displacement of the entire engine, which is the cylinder's displacement times the number of cylinders. The displacement of an engine can give you a good idea of how much power it can produce.

For motorcycles, the displacement is often part of the name. For example, the Kawasaki Ninja 650 has about 650 cubic centimeters of displacement.

1.7   The Ford Model T and Ethanol

The Ford Model T was the first mass-produced car. It came out in 1908 and remained in production until 1927. It had a four-cylinder engine that would run on ethanol, benzene, or kerosene. For the purposes of this exercise, let's assume you are running yours on ethanol.

A molecule of ethanol has 2 carbon atoms, 6 hydrogen atoms, and 1 oxygen atom. The oxygen in the atmosphere is O_2. When one molecule of ethanol combines with 3 molecules

of O_2, 2 molecules of CO_2 and 3 molecules of H_2O are created. A large amount of heat is also created — 1330 kilojoules for every mole of ethanol burned.

The engine block is usually very hot once the engine has been running. That is important because the ethanol will be completely vaporized at that temperature.

In any sample of air, 21

Exercise 1   **Fuel Mix for the Model T**

On the Model T, a carburetor mixed the fuel and air before it went into the cylinder. The question to answer in this exercise is: How rich should the mix be at sea level (100 kPa)?

On the Wikipedia page for the Model T, we see the following facts:

- Cylinder bore: 9.525 cm

- Piston stroke: 10.16 cm

You can assume that the air/fuel mixture is 80° C before the pre-burn compression starts. (Thus, the ethanol, which boils at 78° C, is in its vapor phase.)

The questions, then, are:

- What is the displacement of a single cylinder?

- How many moles of gas (80° C and 100 kPa) will get sucked through the intake valve?

- How many moles of vaporized ethanol should be part of that?

- How many moles of CO_2 and H_2O are created in each burn?

- How much heat is created in each burn?

(This exercise has a lot of steps, but nothing you don't already know. You will need the Ideal Gas Law to figure out how much many moles of air gets dragged into the cylinder.)

1.8   Compression Ratio

Most of the inefficiency of a motor is heat that escapes through the exhaust valve. If your piston stroke were long enough, you could keep increasing the volume (which would cool the gases inside) until the gases inside were the same temperature as the outside world. Then there would be no wasted heat in the exhaust.

For this reason, generally, engines with a higher compression ratios tend to waste less energy through the heat of the exhaust. The Model T had a compression ratio close to 4:1. Modern car engines typically have compression ratios between to 8:1 and 12:1.

Cars with especially high compression ratios often require fuels with a lot of kilojoules per mole — we say *high octane*. If the fuel does not have enough energy, the engine makes loud knocking noises, as the pistons do not have enough energy to push through their entire stroke.

It turned out that an easy way to boost the octane of the gasoline was to add a chemical called tetraethyl lead. Gasoline containing tetraethyl lead was known at "Leaded Gasoline", and was intended to prevent the knocking. It is difficult to overstate the damages caused by putting large amounts of lead in the air. Gradually, starting with Japan in 1986, every country in the world has banned leaded gasoline.

1.9   The Choke and Direct Fuel Injection

Most cars built before 1990 will have a carburetor, which ensures that the ratio between fuel and oxygen is constant, regardless of the amount of fuel released by the throttle.

If you go to start an old car on a cold morning, the cold engine will not vaporize the fuel properly, and the engine may not have enough power to start. For this reason, most carburetors have a *choke value* that makes the mix richer. (If you pull the choke valve, be sure to push it back after the engine warms up.)

The carburetor was a common source of engine problems and inefficiencies. Starting in the 1990s, car engines started using direct fuel injection. Air still came in through the intake manifold, but fuel was sprayed directly into the cylinder by a fuel injection system.

In modern cars, the fuel injection system is controlled by a computer (an *Engine Control Module* or ECM), which delivers the fuel at the perfect time with the perfect amount based on environmental variables like the temperature of the engine and the barometric pressure (usually related to that altitude at which the engine is operating).

org/) *for more details.*

Answers to Exercises

Answer to Exercise 1 (on page 8)

The pre-compression temperature is $80irc$ C $+ 273.15 = 353.15°$ K.

The radius of the cylinder is $9.535/2 = 4.7625$ cm.

The area of a cross section of the cylinder is $\pi r^2 = \pi(4.7625)^2 \approx 71.26$ ml.

So, the change in volume between the minimum and maximum volume is $(71.26)(10.16) = 724$ ml, or 0.724 liters.

(With four cylinders, the total displacement of a Model T is thus $(4)(724) = 2,896$ cc.)

Now we use the ideal gas to figure out how many moles of gas will fit into 0.724 liters at 100 kPa and $353.15°$ K.

$$n = \frac{PV}{rT} = \frac{(100)(0.724)}{(8.314)(353.15)} = 0.02466 \text{ moles of air+fuel}$$

So, if we suck n_a moles of air and n_e moles of vaporized ethanol in to the cylinder:

$$n_a + n_e = 0.02466$$

So

$$n_a = 0.02466 - n_e$$

21% of n_a is O_2:

$$n_{O_2} = 0.21 n_a = 0.21(0.02466 - n_e) = 0.005178 - 0.21 n_e$$

For a clean burn, we need 3 times as many O_2 molecules as ethanol molecules. Thus:

$$3n_e = n_{O_2} = 0.005178 - 0.21n_e$$

Solving for n_e:

$$n_e = \frac{0.005178}{3.21} = 0.001613 \text{ moles of ethanol}$$

For every molecule of ethanol that burns we get 2 molecules of CO_2: 0.003226 moles.

For every molecule of ethanl that burns we get 3 molecules of H_2OI: 0.004839 moles.

How much heat? $(0.001613)(1330) = 2.145$ kilojoules from each burn.

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