12.4 Applications of Thermodynamics: Heat Engines, Heat Pumps, and Refrigerators

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Explain how heat engines, heat pumps, and refrigerators work in terms of the laws of thermodynamics
- Describe thermal efficiency
- Solve problems involving thermal efficiency

Teacher Support

Teacher Support The learning objectives in this section will help your students master the following standards:

- (6) Science concepts. The student knows that changes occur within a physical system and applies the laws of conservation of energy and momentum. The student is expected to:
  - (G) analyze and explain everyday examples that illustrate the laws of thermodynamics, including the law of conservation of energy and the law of entropy.

Section Key Terms

Teacher Support

Teacher Support [BL][OL][AL] Return again to the discussion of efficiency that was begun at the start of the module. Review the ideal gas law, laws of thermodynamics, and entropy.

[OL] Ask students whether they can explain the limits on efficiency in terms of what they have now learned.

Heat Engines, Heat Pumps, and Refrigerators

In this section, we'll explore how heat engines, heat pumps, and refrigerators operate in terms of the laws of thermodynamics.

One of the most important things we can do with heat is to use it to do work for us. A heat engine does exactly this—it makes use of the properties of thermodynamics to transform heat into work. Gasoline and diesel engines, jet engines, and steam turbines that generate electricity are all examples of heat engines.

Figure 12.13 illustrates one of the ways in which heat transfers energy to do work. Fuel combustion releases chemical energy that heat transfers throughout the gas in a cylinder. This increases the gas temperature, which in turn increases the pressure of the gas and, therefore, the force it exerts on a movable piston. The gas does work on the outside world, as this force moves the piston through some distance. Thus, heat transfer of energy to the gas in the cylinder results in work being done.

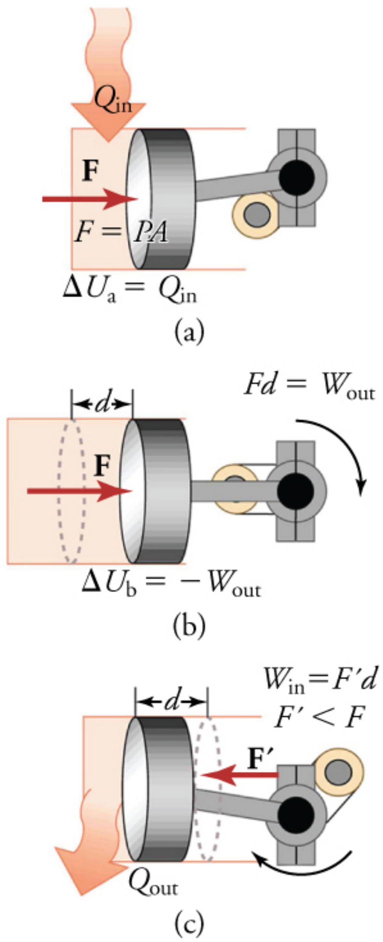

Figure 12.13 (a) Heat transfer to the gas in a cylinder increases the internal energy of the gas, creating higher pressure and temperature. (b) The force exerted on the movable cylinder does work as the gas expands. Gas pressure and temperature decrease during expansion, indicating that the gas's internal energy has decreased as it does work. (c) Heat transfer of energy to the environment

further reduces pressure in the gas, so that the piston can more easily return to its starting position.

To repeat this process, the piston needs to be returned to its starting point. Heat now transfers energy from the gas to the surroundings, so that the gas's pressure decreases, and a force is exerted by the surroundings to push the piston back through some distance.

A cyclical process brings a system, such as the gas in a cylinder, back to its original state at the end of every cycle. All heat engines use cyclical processes.

Heat engines do work by using part of the energy transferred by heat from some source. As shown in Figure 12.14, heat transfers energy, Q_{h}, from the high-temperature object (or hot reservoir), whereas heat transfers unused energy, Q_{c}, into the low-temperature object (or cold reservoir), and the work done by the engine is W. In physics, a *reservoir* is defined as an infinitely large mass that can take in or put out an unlimited amount of heat, depending upon the needs of the system. The temperature of the hot reservoir is T_{h}, and the temperature of the cold reservoir is T_{c} .

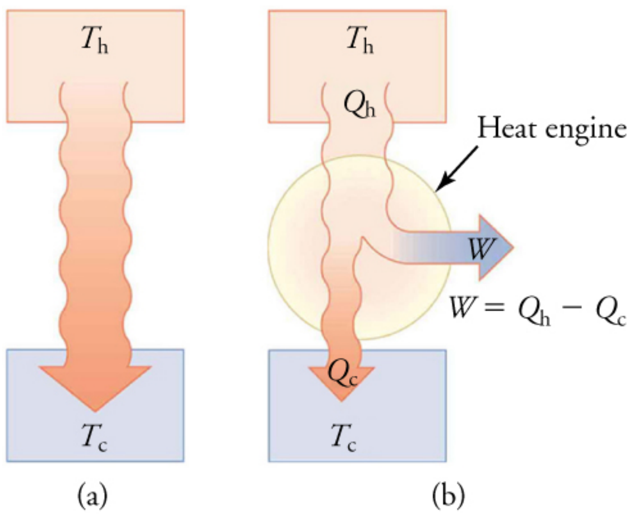

Figure 12.14 (a) Heat transfers energy spontaneously from a hot object to a cold one, as is consistent with the second law of thermodynamics. (b) A heat engine, represented here by a circle, uses part of the energy transferred by heat to do work. The hot and cold objects are called the hot and cold reservoirs. Q_{h} is the heat out of the hot reservoir, W is the work output, and Q_{c} is the unused heat into the cold reservoir.

As noted, a cyclical process brings the system back to its original condition at the end of every cycle. Such a system's internal energy, U, is the same at the beginning and end of every cycle—that is, $\Delta U = 0$. The first law of thermodynamics states that $\Delta U = Q - W$, where Q is the *net* heat transfer during the cycle, and W is the *net* work done by the system. The net heat transfer is the energy transferred in by heat from the hot reservoir minus the amount that is transferred out to the cold reservoir ($Q = Q_{\mathrm{h}} - Q_{\mathrm{c}}$). Because there is no change in internal energy for a complete cycle ($\Delta U = 0$), we have

$$0 = Q - W,$$

12.19

so that

$$W = Q.$$

12.20

Therefore, the net work done by the system equals the net heat into the system, or

$$W = Q_{\mathrm{h}} - Q_{\mathrm{c}}$$

12.21

for a cyclical process.

Because the hot reservoir is heated externally, which is an energy-intensive process, it is important that the work be done as efficiently as possible. In fact, we want W to equal Q_{h}, and for there to be no heat to the environment (that is, $Q_{\mathrm{c}} = 0$). Unfortunately, this is impossible. According to the second law of thermodynamics, heat engines cannot have perfect conversion of heat into work. Recall that entropy is a measure of the disorder of a system, which is also how much energy is unavailable to do work. The second law of thermodynamics requires that the total entropy of a system either increases or remains constant in any process. Therefore, there is a minimum amount of Q_{h} that cannot be used for work. The amount of heat rejected to the cold reservoir, Q_{c}, depends upon the efficiency of the heat engine. The smaller the increase in entropy, ΔS , the smaller the value of Q_{c}, and the more heat energy is available to do work.

Heat pumps, air conditioners, and refrigerators utilize heat transfer of energy from low to high temperatures, which is the opposite of what heat engines do. Heat transfers energy Q_{c} from a cold reservoir and delivers energy Q_{h} into a hot one. This requires work input, W, which produces a transfer of energy by heat. Therefore, the total heat transfer to the hot reservoir is

$$Q_{\mathrm{h}} = Q_{\mathrm{c}} + W.$$

12.22

The purpose of a heat pump is to transfer energy by heat to a warm environment, such as a home in the winter. The great advantage of using a heat pump to keep your home warm rather than just burning fuel in a fireplace or furnace is that a heat pump supplies $Q_{\mathrm{h}} = Q_{\mathrm{c}} + W$. Heat Q_{c} comes from the outside air, even at a temperature below freezing, to the indoor space. You only pay for W, and you get an additional heat transfer of Q_{c} from the outside at no cost. In many cases, at least twice as much energy is transferred to the heated space as is used to run the heat pump. When you burn fuel to keep warm, you pay for all of it. The disadvantage to a heat pump is that the work input (required by the second law of thermodynamics) is sometimes more expensive than simply burning fuel, especially if the work is provided by electrical energy.

The basic components of a heat pump are shown in Figure 12.15. A working fluid, such as a refrigerant, is used. In the outdoor coils (the evaporator), heat Q_c enters the working fluid from the cold outdoor air, turning it into a gas.

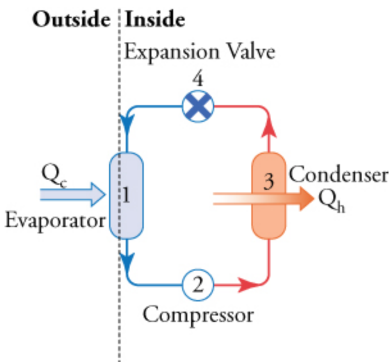

Figure 12.15 A simple heat pump has four basic components: (1) an evaporator, (2) a compressor, (3) a condenser, and (4) an expansion valve. In the heating mode, heat transfers Q_c to the working fluid in the evaporator (1) from the colder, outdoor air, turning it into a gas. The electrically driven compressor (2) increases the temperature and pressure of the gas and forces it into the condenser coils (3) inside the heated space. Because the temperature of the gas is higher than the temperature in the room, heat transfers energy from the gas to the room as the gas condenses into a liquid. The working fluid is then cooled as it flows back through an expansion valve (4) to the outdoor evaporator coils.

The electrically driven compressor (work input W) raises the temperature and pressure of the gas and forces it into the condenser coils that are inside the heated space. Because the temperature of the gas is higher than the temperature inside the room, heat transfers energy to the room, and the gas condenses into a liquid. The liquid then flows back through an expansion (pressure-reducing) valve. The liquid, having been cooled through expansion, returns to the outdoor evaporator coils to resume the cycle.

The quality of a heat pump is judged by how much energy is transferred by heat into the warm space (Q_h) compared with how much input work (W) is required.

Teacher Support

Teacher Support

Misconception Alert

Remember that refrigerators and air conditioners do not *create* cold. They merely transfer heat from the inside to the outside.

Revisit the ideal gas law, laws of thermodynamics, and entropy. Use these to understand the workings of air conditioners and refrigerators. This will also give you the opportunity to assess your understanding of these concepts. Both refrigerators and air conditioners use chemicals that can easily change phase from liquid to gas and back. The chemical is present in a closed circuit of tubing. Initially, it is in a gaseous state. The compressor works to squeeze the gas particles of the chemical closer together, creating high pressure. Following the ideal gas law, as pressure increases, so does temperature. This hot, dense gas spreads out in the small pipes or fins of the condenser, which is located on the outside part of the air conditioner (and backside of a refrigerator). The fins come in contact with outside air, which is cooler than the compressed chemical, and hence, as entropy indicates, heat transfers energy from the hot condenser to the relatively cooler air. The result is that the gas cools and condenses into a liquid. This liquid is then allowed to go to an evaporator through a tiny, narrow hole. On the other side of the hole, the gas spreads out (entropy increases), and its pressure drops. Consequently, obeying the ideal gas law, its temperature decreases as well. A fan blows air over this now-cool evaporator and into the room or refrigerator (Figure 12.16).

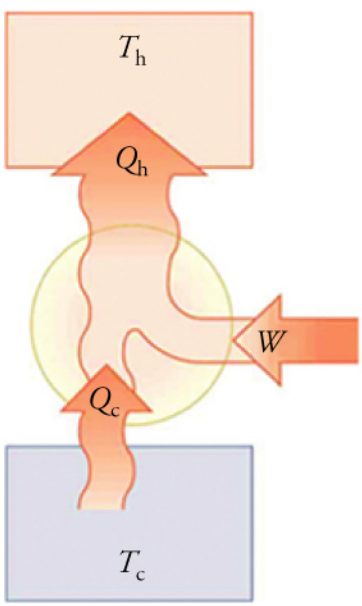

Figure 12.16 Heat pumps, air conditioners, and refrigerators are heat engines operated backward. Almost every home contains a refrigerator. Most people don't realize that they are also sharing their homes with a heat pump.

Air conditioners and refrigerators are designed to cool substances by transferring energy by heat Q_{c} out of a cool environment to a warmer one, where heat Q_{h} is given up. In the case of a refrigerator, heat is moved out of the inside of the fridge into the surrounding room. For an air conditioner, heat is transferred outdoors from inside a home. Heat pumps are also often used in a reverse setting to cool rooms in the summer.

As with heat pumps, work input is required for heat transfer of energy from cold to hot. The quality of air conditioners and refrigerators is judged by how much energy is removed by heat Q_{c} from a cold environment, compared with how much work, *W*, is required. So, what is considered the energy benefit in a heat pump, is considered waste heat in a refrigerator.

Thermal Efficiency

In the conversion of energy into work, we are always faced with the problem of getting less out than we put in. The problem is that, in all processes, there is some heat Q_{c} that transfers energy to the environment—and usually a very significant amount at that. A way to quantify how efficiently a machine runs is through a quantity called thermal efficiency.

We define thermal efficiency, *Eff*, to be the ratio of useful energy output to the energy input (or, in other words, the ratio of what we get to what we spend). The efficiency of a heat engine is the output of net work, *W*, divided by heat-transferred energy, Q_{h}, into the engine; that is

$Eff = \frac{W}{Q_{\mathrm{h}}}$.

An efficiency of 1, or 100 percent, would be possible only if there were no heat to the environment ($Q_{\mathrm{c}} = 0$).

Tips For Success

All values of heat (Q_{h} and Q_{c}) are positive; there is no such thing as negative heat. The *direction* of heat is indicated by a plus or minus sign. For example, Q_{c} is out of the system, so it is preceded by a minus sign in the equation for net heat.

$Q = Q_{\mathrm{h}} - Q_{\mathrm{c}}$

12.23

Solving Thermal Efficiency Problems

Worked Example

Daily Work Done by a Coal-Fired Power Station and Its Efficiency
A coal-fired power station is a huge heat engine. It uses heat to transfer energy from burning coal to do work to turn turbines, which are used then to generate electricity. In a single day, a large coal power station transfers 2.50×10^{14}J by

heat from burning coal and transfers 1.48×10^{14}J by heat into the environment. (a) What is the work done by the power station? (b) What is the efficiency of the power station?

Strategy

We can use $W = Q_{\mathrm{h}} - Q_{\mathrm{c}}$ to find the work output, W, assuming a cyclical process is used in the power station. In this process, water is boiled under pressure to form high-temperature steam, which is used to run steam turbine-generators and then condensed back to water to start the cycle again.

Solution

Work output is given by

$W = Q_{\mathrm{h}} - Q_{\mathrm{c}}.$

12.24

Substituting the given values,

$W = 2.50 \times 10^{14}\mathrm{J} - 1.48 \times 10^{14}\mathrm{J} = 1.02 \times 10^{14}\mathrm{J}.$

12.25

Strategy

The efficiency can be calculated with $Eff = \frac{W}{Q_{\mathrm{h}}}$, because Q_{h} is given, and work, W, was calculated in the first part of this example.

Solution

Efficiency is given by

$Eff = \frac{W}{Q_{\mathrm{h}}}.$

12.26

The work, W, is found to be 1.02×10^{14}J, and Q_{h} is given ($2.50 \times 10^{14}\mathrm{J}$), so the efficiency is

$Eff = \frac{1.02 \times 10^{14}\mathrm{J}}{2.50 \times 10^{14}\mathrm{J}} = 0.408$, or 40.8%.

12.27

Discussion

The efficiency found is close to the usual value of 42 percent for coal-burning power stations. It means that fully 59.2 percent of the energy is transferred by heat to the environment, which usually results in warming lakes, rivers, or the ocean near the power station and is implicated in a warming planet generally. While the laws of thermodynamics limit the efficiency of such plants—including plants fired by nuclear fuel, oil, and natural gas—the energy transferred by heat to the environment could be, and sometimes is, used for heating homes or for industrial processes.

Practice Problems

17.

A heat engine is given 120\,\text{J} by heat and releases 20\,\text{J} by heat to the environment. What is the amount of work done by the system?

a. {-100}\,\text{J}
b. {-60}\,\text{J}
c. 60\,\text{J}
d. 100\,\text{J}

18.

A heat engine takes in 6.0 kJ from heat and produces waste heat of 4.8 kJ. What is its efficiency?

a. 25 percent
b. 2.50 percent
c. 2.00 percent
d. 20 percent

Check Your Understanding

Teacher Support

Teacher Support Use these questions to assess student achievement of the section's learning objectives. If students are struggling with a specific objective, these questions will help identify which and direct students to the relevant content.

19.

What is a heat engine?

a. A heat engine converts mechanical energy into thermal energy.
b. A heat engine converts thermal energy into mechanical energy.
c. A heat engine converts thermal energy into electrical energy.
d. A heat engine converts electrical energy into thermal energy.

20.

Give an example of a heat engine.

a. A generator
b. A battery
c. A water pump
d. A car engine

21.

What is thermal efficiency?

a. Thermal efficiency is the ratio of work input to the energy input.
b. Thermal efficiency is the ratio of work output to the energy input.
c. Thermal efficiency is the ratio of work input to the energy output.
d. Thermal efficiency is the ratio of work output to the energy output.

22.

What is the mathematical expression for thermal efficiency?

a. Eff = \frac{Q_{\text{h}}}{Q_{\text{h}} - Q_c}
b. Eff = \frac{Q_{\text{h}}}{Q_c}
c. Eff = \frac{Q_{\text{c}}}{Q_{\text{h}}}
d. Eff = \frac{Q_{\text{h}} - Q_{\text{c}}}{Q_{\text{h}}}