15-1 The First Law of Thermodynamics

Consider a cylinder of ideal gas sealed with a piston, a system we examined in Chapter 14. Let's explore what happens to the system's energy when the temperature increases.

Figure 15.1: A cylinder sealed with a piston that can move up or down without friction. The cylinder is initially at room temperature, 20°C.

EXPLORATION 15.1 – Adding heat to a cylinder

A cylinder of ideal gas, as in Figure 15.1, is sealed with a piston that can move up or down without friction. The top of the piston is exposed to the atmosphere. The ideal gas in the cylinder is initially at room temperature, 20°C. The cylinder is then placed in a water bath that is maintained at a constant temperature of 90°C.
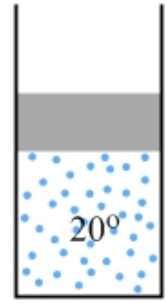
Step 1 – *Describe qualitatively what happens to this gas system when it is placed in the water bath.*
Because the temperature of the gas in the cylinder is lower than that of the water bath, heat will be transferred from the water into the gas. This is shown in Figure 15.2. This transfer of energy will continue until the gas in the cylinder reaches 90°C, the same temperature as the water bath. At that point, thermal equilibrium will be reached and the energy transfer will stop.
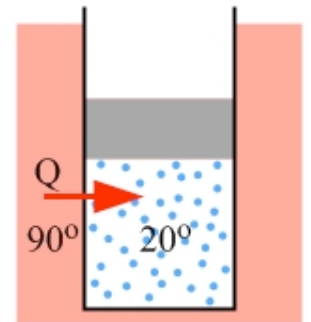

Figure 15.2: When the cylinder is placed in a water bath that is maintained at a temperature higher than the gas, heat is naturally transferred from the water bath into the cylinder until thermal equilibrium is reached.

Step 2 – *Describe what happens to the energy transferred as heat from the water bath to the ideal gas.* Increasing the temperature of the gas means increasing the internal energy of the gas. Thus, some of the heat Q transferred to the gas causes a change in internal energy, ΔE_{int}. However, something else must change for the gas to satisfy the condition set by the ideal gas law, $PV = nRT$. As we discussed in Chapter 14, in a cylinder in which the piston is free to move, the pressure is determined by the forces on the piston's free-body diagram (see Figure 15.3).

When the gas temperature reaches 90°C, the piston is at a new equilibrium position, but the pressure in the cylinder is the same as it was before – nothing has changed on the free-body diagram. Thus, to satisfy the ideal gas law, the volume occupied by the gas increases when the pressure increases. This is shown in Figure 15.4. The expanding gas does a positive amount of work W, exerting an upward force and causing an upward displacement of the piston. Like the change in internal energy, the work W comes from the heat Q transferred from the water bath into the gas. Thus, some of the transferred heat goes into raising the internal energy of the system, and some goes into doing work.

Figure 15.3: Applying Newton's second law to the free-body diagram tells us that, with the piston at equilibrium, the pressure of the gas is given by $P = P_{atm} + mg / A$, where A is the area of the top or bottom of the piston.
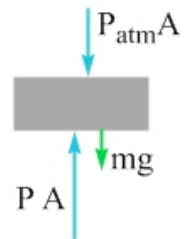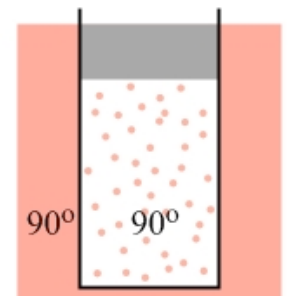

Figure 15.4: When thermal equilibrium is reached, the gas occupies a larger volume because the temperature is higher, maintaining a constant pressure.

Key Idea: Heat transferred between a system and its surroundings can be transformed into two other forms of energy. Some (or even all, in certain cases) of the heat goes into changing the internal energy of the gas (corresponding to a temperature change) while the remaining heat goes into doing work. This statement of energy conservation is the first law of thermodynamics, which is defined more formally below.   **Related End-of-Chapter Exercises: 1 and 13.**

The first law of thermodynamics is a statement of energy conservation as it relates to a thermodynamic system. Heat, which is energy transferred into or out of a system, can be transformed into (or come from) some combination of a change in internal energy of the system and the work done by (or on) the system.

$$Q = \Delta E_{int} + W \ .$$ (Equation 15.1: **The First Law of Thermodynamics**)

Q is positive when heat is added to a system, and negative when heat is removed.
ΔE_{int} is positive when the temperature of a system increases, and negative when it decreases.

W is positive when a system expands and does work, and negative when the system is compressed.

EXAMPLE 15.1 – Some numerical calculations

Let's do two numerical calculations related to Exploration 15.1. Let's say that 3500 J is transferred to the cylinder as heat. The work done by the gas while the heat is being transferred is 1400 J. (a) Calculate the change in internal energy experienced by the gas in the cylinder. (b) If the change in internal energy can be calculated, in this case, using the equation $\Delta E_{int} = (3/2)nR\,\Delta T$, calculate the number of moles of gas in the cylinder.

SOLUTION

(a) We can calculate the change in internal energy by re-arranging the equation for the first law.
$$\Delta E_{int} = Q - W = 3500 \text{ J} - 1400 \text{ J} = 2100 \text{ J} \ .$$

(b) Now, we can solve for the number of moles by re-arranging the equation that was given for the change in internal energy.

$$n = \frac{(2/3)\Delta E_{int}}{R\,\Delta T} = \frac{(2/3)\,2100 \text{ J}}{(8.31 \text{ J/mol K})(+70\text{K})} = \frac{1400 \text{ J}}{(8.31 \text{ J/mol K})(+70\text{K})}$$

$$n = \frac{20 \text{ J/K}}{8.31 \text{ J/mol K}} = 2.4 \text{ moles}$$

Cylinder 1

Essential Question 15.1: Figure 15.5 shows two cylinders containing equal amounts of the same ideal gas in the same initial state – the gas in the two cylinders has the same pressure, volume, and temperature. The difference between them is that, in cylinder 1, the piston sealing the cylinder is free to move up or down without friction, while the piston in cylinder 2 is fixed so the volume occupied by the gas is constant. Both cylinders are initially at 20°C, but are then placed in a water bath that is maintained at a constant temperature of 80°C and allowed to come to equilibrium. In this process, which cylinder has more heat transferred to it? Which cylinder experiences a larger change in internal energy?
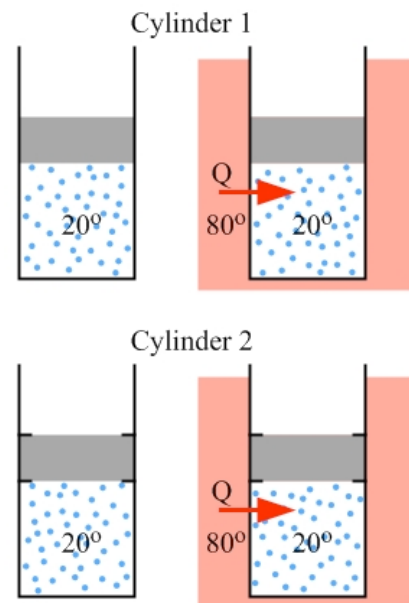
Cylinder 2

Figure 15.5: The piston in cylinder 1 is free to move without friction, while the piston in cylinder 2 is fixed in place so the gas occupies a constant volume.