HEAT, WORK AND TEMPERATURE

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Reference: Daniel V. Schroeder, *An Introduction to Thermal Physics*, (Addison-Wesley, 2000) - Problems 1.26 - 1.30.

In thermodynamics, temperature, heat and work are all related to energy and energy flow. The temperature is related to the energy content of a substance (a precise definition will have to wait); basically, the more energy (well, kinetic energy, anyway) a substance contains, the higher its temperature. Heat and work are both related to energy flow from one body or area of a body to another. Thus temperature is essentially a static property; it doesn't depend on energy moving around. Heat and work are dynamic properties, as they exist only when energy is flowing.

Heat is the spontaneous flow of energy from one body to another as a result of a temperature difference. Work is the flow of energy into or out of a body due to any other cause.

Example 1. In an electric kettle, the heating element is essentially a resistor which gets hot when a current is passed through it. Thus energy is flowing into the resistor, but it is as a result of electric current, not a temperature difference, so the electric current (or, to be more precise, the generator that produces the electricity) is doing work on the resistor. Although in common usage, we would say that the resistor 'heats up', using the definitions of heat and work in thermodynamics, there is no heat involved here; it is all work.

The heating of the water being boiled, however, is a heat flow as it results from energy flowing spontaeously from the resistor into the water as a result of the temperature difference between the resistor and the water.

Example 2. Any process in which work is done on a body can raise the temperature even if no heat flows. The heating of the resistor in the kettle is an example. It is also possible to add heat to a system without raising its temperature. When the water in the kettle reaches its boiling point, for example, the temperature of the water doesn't increase any further. The heat is used to vaporize the water at a constant temperature.

Using Schroeder's notation, heat flowing into a system is represented by Q and work done on a system by W, so the change in thermal energy is

$$\Delta U = Q + W \tag{1}$$

This is known as the *first law of thermodynamics*, although it's more commonly known as conservation of energy. The SI unit of energy is the Joule, but the older unit of the *calorie* is also often used. A calorie is the energy need to raise the temperature of 1 gram (or equivalently, 1 cm^3) of water by one kelvin. One calorie is equivalent to 4.186 J.

Example 3. Suppose we put a mug containing 250 ml of cold (5° C) water in a 600 watt microwave. How long will it take to boil the water, assuming all the energy goes into the water? We need to raise the temperature by 95 K, so the energy required is

$$\Delta U = 250 \times 95 \times 4.186 = 99417.5 \text{ J} \tag{2}$$

One watt is one joule per second, so it will take

$$t = \frac{99417.5}{600} = 165.7 \text{ s} = 2.76 \text{ minutes} \tag{3}$$

Example 4. If we place a mug of water at room temperature (20°C) on a table, then leave the room for 10 minutes, then come back, and we find that the temperature of the water is now 25°C, we can't really say anything about how it got that way without knowing a bit more. For example, the 'room temperature' might actually have been higher than 20°, the water might have had work done on it (by having a heating element placed in it), or someone else might have poured out the original water and replaced it with warmer water. Only in the first case would heat be involved. As Schroeder says, it's a trick question.

Example 5. In this problem, Schroeder asks us to put some water in a bottle, measure its temperature, and then shake it for several minutes, after which we measure the temperature again to see if the work we've done on the water has actually raised its temperature. I didn't actually do this experiment because I don't have a thermometer that can be put in water (being too much of a techy, all my thermometers are electronic with liquid crystal readouts, and they wouldn't want to be immersed in water). However, we can get a rough idea of how much of a temperature change would result from a crude calculation.

Suppose we exert enough force on the bottle to keep its acceleration at around 1g (10 m s^{-2}) and that the constant back-and-forth motion of shaking the bottle causes the work done on the bottle to be converted into heat. If we have 100 cm^3 of water in the bottle, and we complete one back-and-forth cycle of the shake per second, and the distance over which we shake it is $d = 10$ cm $= 0.1$ m, then the work done per second is

$$\Delta U = mg \times 2d = 0.1 \text{ kg} \times 10 \text{ m s}^{-2} \times 2 \times 0.1 \text{ m} = 0.2 \text{ J} \tag{4}$$

The temperature rise of the 100 cm^3 of water per second is then

$$\Delta T=\frac{0.2}{4.186\times100}=4.78\times10^{-4}\text{ K} \tag{5}$$

If we shook the bottle for, say, 10 minutes, we'd expect the temperature to rise by

$$\Delta T_{10}=4.78\times10^{-4}\times10\times60=0.29\text{ K} \tag{6}$$

I doubt this would be measureable, since the bottle would probably lose heat to the surrounding air at around the same rate (just a guess). We could try shaking the bottle faster and/or with a larger acceleration, and we might get the temperature increase high enough (say over a degree) to measure.

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