Applied Physics For Engineers

Contents:

Work, Energy, and Power

Work is the expenditure of energy to overcome some restraint or to achieve some change in the physical state of a body. Examples include the work performed by a man when expending energy to lift a weight above his head, and the action of a steam-driven piston when water is made to boil by consumption of heat energy. Energy is often defined as the ability to do work. *Energy and work have the same units*. In the SI system, those units are *joules* (J). Heat is a particularly important form of energy in the study of electricity, not only because it affects the electrical properties of materials, but also because it is *liberated* whenever electrical current flows. This liberation of heat is in fact the conversion of electrical energy to heat energy. To gain some appreciation for the magnitude of a joule of heat energy, consider that it would require about 90,000 J to heat a cup of water from room temperature to boiling.

Power is the *rate* at which energy is expended, or the rate at which work is performed. Since energy and work both have the units of joules, it follows that power, being a rate, has the units joules/second. Returning to the boiling-water example, suppose that all the heat required (all 90,000 J) could be supplied to the cup of water in 1 s. Then the power would be the very large value 90,000 J/s. On the other hand, if the water were allowed to come to a very slow boil by supplying the same amount of heat over a period of 30 min, the power would be only 50 J/s. Note that the total amount of heat energy is the same in each case, and that in each case the water comes to a boil. However, the power is quite different, because the rates at which heat is supplied are different. In the SI system, the units joules/second are called *watts*. Thus, the watt is the SI unit of power. In general,

$$P = \frac{W}{t} \quad \text{watts} \tag{3.3}$$

where W is the total number of joules of work performed, or the total joules of energy expended, in t seconds. We will use the symbol W to stand for energy as well as work, to avoid confusion with the symbol E for voltage.

Example 3.3

How much heat energy is produced by a 1.5-kW electric heater when it is operated for 30 min?

SOLUTION From equation (3.3),

$$W = Pt = (1.5 \times 10^3 \text{ W})(30 \text{ min})\left(\frac{60 \text{ s}}{1 \text{ min}}\right) = 2.7 \times 10^6 \text{ J}$$

Drill Exercise 3.3

How long would it take the heater in Example 3.3 to produce 0.6 MJ of heat energy?

ANSWER: 400 s.

□

When electric current flows through resistance, electric energy is converted to heat energy at a rate that depends on the voltage across the resistance and on the value of current through it:

$$P = VI \qquad \text{watts} \tag{3.4}$$

where V is the voltage across the resistance and I is the current through it. Note that the product of volts and amperes is watts, or joules per second. Although not technically correct usage, it is conventional to say that resistance "dissipates power," meaning that it dissipates (liberates) heat at a certain rate.

By substituting $V = IR$ from Ohm's law into equation (3.4), we find another useful expression for electrical power:

$$P = VI = (IR)I = I^2R \qquad \text{watts} \tag{3.5}$$

We can also substitute $I = V/R$ into equation (3.4) and obtain still another expression for power:

$$P = VI = V\left(\frac{V}{R}\right) = \frac{V^2}{R} \qquad \text{watts} \tag{3.6}$$

Example 3.4

Find the power in the resistance shown in Figure 3.7 using each of equations (3.4), (3.5), and (3.6).

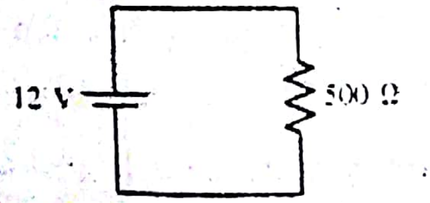

FIGURE 3.7 (Example 3.4)

SOLUTION By Ohm's law,

$$I = \frac{V}{R} = \frac{12\text{ V}}{500\ \Omega} = 24\text{ mA}$$

By equation (3.4),

$$P = VI = (12\text{ V})(24\text{ mA}) = 288\text{ mW}$$

By equation (3.5),

$$P = I^2R = (24 \times 10^{-3}\text{A})^2(500\ \Omega) = 288\text{ mW}$$

By equation (3.6),

$$P = \frac{V^2}{R} = \frac{(12\text{ V})^2}{500\ \Omega} = 288\text{ mW}$$

Drill Exercise 3.4

What voltage connected across the 500-Ω resistance in Figure 3.7 would cause the power dissipation to be 5 W?

ANSWER: 50 V. □

The rate at which resistance liberates heat energy equals the rate at which energy is supplied to the resistance by a voltage source. Loosely speaking, the power "delivered" to the resistance equals the power dissipated in the resistance. There is no resistance associated with an (ideal) voltage source, so the power delivered by the source can only be calculated using equation (3.4): $P = EI$ watts, where E is the terminal voltage and I is the current furnished by the source. In Example 3.4, the power delivered by the 12-V source is $P = EI = (12\text{ V})(24\text{ mA}) = 288\text{ mW}$, which equals the power dissipated in the 500-Ω resistance.

Kilowatt-hours

In the electrical power industry, the unit of power most often used is the kilowatt (1 kW = 1000 W). The unit of energy used is the total energy delivered or consumed in 1 hour when the rate of delivery or consumption is 1 kW. That amount of energy is 1 *kilowatt-hour* (kWh).

$$\text{kWh} = (P\text{ in kW}) \times (t\text{ in hours}) \tag{3.7}$$

The kilowatt-hour is *not* an SI unit.

Note that customers of a power company are billed for the total amount of *energy* consumed, in kWh, not for power. As illustrated in the next example, the total energy consumed by various electrical "loads" can be calculated using equation (3.7).

Example 3.5

If a power company charges \$0.10 for each kWh of energy delivered to a customer, find the total cost of operating a 500-W television set for 2 h, six 75-W light bulbs for 4 h, a 1500-W clothes drier for 30 min, and a 2-kW electric heater for 45 min.

SOLUTION

The total energy consumed by each load is computed using equation (3.7):

Television: (0.5 kW)(2 h)		1 kWh
Light bulbs: (6)(0.075 kW)(4 h)		1.8 kWh
Clothes drier: (1.5 kW)(0.5 h)		0.75 kWh
Heater: (2 kW)(0.75 h)		1.5 kWh
	Total	5.05 kWh
Total cost = (5.05 kWh)($0.10/kWh)	=	$0.505

Drill Exercise 3.5

If electrical energy costs $0.12/kWh, for how long could a 900-W oven be operated without costing more than 36 cents?

ANSWER: $3\frac{1}{3}$ h.