Energy Transformations and Efficiency

**Required Waste Power**

When humans use energy, they follow the general principle depicted in the illustration below. We have a passive energy source, usually a fuel, from which we withdraw “useful power” with some device that transforms the energy from one form to another. Inextricably and unavoidably some of the energy is also transformed along another path, “waste power.” It would be great if all of the transformed energy could be converted into the “useful power,” but the laws of nature prevent this; nature requires that part of the power produced must be waste power (more on this later).

![Energy Transformation Diagram](image)

Efficiency measures the fraction of the total energy (or total power) that becomes useful energy (or useful power) in the transformation process. The definition for efficiency is

\[
\text{Efficiency} = \frac{\text{Useful Power}}{\text{Useful Power} + \text{Waste Power}} \tag{9}
\]

The average efficiency over an extended period of processing the transformation may be found from a similar expression,

\[
\text{Average Efficiency} = \frac{\text{Useful Energy}}{\text{Useful Energy} + \text{Waste Energy}} \tag{10}
\]

Obvious causes of waste energy are friction in mechanical systems, resistance in electrical systems, and heat loss from thermal systems; we call these dissipative losses, because they dissipate, or squander, energy. These losses can be reduced but never eliminated by using better bearings, larger wires, and increased insulation. There are, however, other forms of waste power that are more fundamentally connected to how the system works, and they are not easily eliminated. In the drawing above, the curved arrow linking Waste Power to Useful Power and labeled Coupled represents those forms of waste power that the system requires to function; we will refer to these as the “Required Waste Power.” The best way to understand required waste power is to examine how several systems actually work and find the required waste power for the systems.

Our first example is a well with an electric pump that lifts water into a storage tank. When the pump is running, water is moving upward in the pipe to reach the storage tank; the useful power in this system is the power used in lifting the water from the well upward against the force of gravity to reach the tank. The water moving upward in the pipe has velocity and, therefore, has kinetic energy; the required waste power in this system is the power being supplied to move the water, its kinetic energy. (Upon reaching the tank the kinetic energy is transformed into turbulent energy and finally through friction into heat. Turbulent energy is the kinetic energy in the swirling motion of the water in the tank.) The useful power and the required waste power are coupled; you cannot fill the tank without moving the water and wasting some of the energy.

We use the equations in the box on the next page to create a mathematical model for the pump; the results are displayed in Figure 3.
In the model for the pump system, we have used the following parameters: \( H = 10 \) meters (~32 feet), \( d = 1 \) inch (solid line) or 2 inches (dashed line), \( F = 1 \text{ gal/min} \) to 41 gal/min. (An outdoor water faucet fully open flows at roughly 10 gallons a minute.)

The pump example exhibits several characteristics of general energy transformation systems. We see that at very small flow the system is very efficient, but as we increase the demand (larger flow) the efficiency rapidly decreases. This is because the useful power \( (P_L) \) is proportional to the velocity \( (F = Av) \), but the required waste power \( (P_M) \) is proportional to velocity cubed. The power lost to friction and the power lost to electrical resistance have a similar relationship to the velocity; if we had included them in the model, the curves in the graph would look much the same but the values for efficiency would be lower. If we were to model an electrical transmission system or an automobile we would get a similar result; increasing the demand decreases the efficiency substantially.

The second system characteristic that we see on the graph is that the two-inch pipe is much more efficient than the one-inch pipe. This is

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**Figure 3.**

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because the flow is proportional to the cross-sectional area of pipe, and when we double the pipe diameter we decrease the velocity by a factor of four for the same flow value. Increasing the diameter also decreases the friction. The performance of the system is better in all aspects when the pipe diameter is increased, so why aren’t the larger pipes always used? They cost more.

This brings us to the third system characteristic that is exemplified here. More efficient systems can be built if we invest more resources in the original design and construction. We have developed the bad habit of trying to keep up-front costs as low as possible; this frequently means that we pay a lot more in the long run.

Our second example will reverse the processes of the first. We have water impounded in a lake behind a dam. Water is allowed to run through a large pipe to a turbine, which turns a generator, which makes electricity. We start with gravitational potential energy in the water, which is converted to kinetic energy in the water, turbine, and generator, which in turn generates electrical energy. This sounds pretty straightforward.

Now, what happens to the water as it leaves the turbine? If it doesn’t continue moving it will stop the turbine, because the water behind it will have no place to go. It’s pretty simple once you think about it; the water coming out must retain some of its original kinetic energy or the system will not work. The power in the water coming out of the turbine is the required waste energy, and the electrical power is the useful power; these two powers are coupled by the basic design of the turbine.

The power produced by the water is proportional to the height of the water above the turbine and to the flow. The required waste power here, \( P_{\text{w}} \), is proportional to the flow cubed and inversely proportional to the output orifice area squared (recall \( F = vA \)). Increasing the area of the output orifice increases the efficiency without decreasing the turbine power, but there is a limit to the output area, which is fixed by the area of the turbine blades.

The total power available for the input flow into the turbine, \( P_i \), is

\[
P_i = \rho g HF
\]

This is the same equation that we had for the power of lift for the pump in the previous example, except here it is the power in the water pressure (\( \rho gH \)) at the bottom of the lake. We can use the equation for the kinetic energy of motion from the previous example to obtain the energy in the outflow from the turbine,

\[
P_o = \frac{1}{2} \rho v^2 F
\]

where \( v \) is the velocity of the water coming out of the turbine. We can write the efficiency equation by subtracting the output flow power from the total available energy

\[
E = \frac{P_i - P_o}{P_i}
\]

Substituting and simplifying we get

\[
E = 1 - \left(\frac{v^2}{2gH}\right)
\]

This can be written as a function of the flow

\[
E = 1 - \left(\frac{F^3}{2gHA_o^3}\right)
\]

where \( A_o \) is the cross-sectional area of the output orifice to the turbine and \( F = vA_o \).

Figure 4 shows the electrical power produced and the efficiency as a function of flow. This model uses \( H = 50 \text{ m} \) and \( d_o = 24 \text{ in} \).

As we have seen in the previous example, efficiency can best be obtained by investing in the original design and construction. As before, we see (1) that increasing the demand on the system decreases the system efficiency, (2) that the system can be designed to be more efficient (larger turbine blades and output orifice), and (3) that the initial cost for a more efficient system will be greater but should produce a long-term payback.

There are important lessons to be learned in these examples that have general application to many energy transformation systems. The required waste power is strongly coupled to the system’s performance because energy transformation systems usually involve flow of a fluid, an electric current, or heat. Our turbine will not
operate unless the water leaves the turbine fast enough to allow new water to enter it. An automobile will not run if the hot exhaust gases are not forced out and fresh air sucked in. Your automobile engine spends three-fourths of its time moving gases around and only one-fourth of its time producing power. A furnace will not work unless we allow hot gases to come out of the flue, taking with them some of the energy.

**Thermal Systems**

If two objects at exactly the same temperature are brought into contact, no heat or thermal energy will flow between them. If one object has a higher temperature, $T_1$, than a second object, $T_2$, thermal energy will flow from the warmer object to the cooler object when the two are brought into contact. This process is thermal conduction; the equation describing the process is very simple:

$$P_c = K \frac{(T_1 - T_2)}{D}$$  

(11)

where $D$ is the distance between $T_1$ and $T_2$, $K$ is a constant called the thermal conductivity of the material between $T_1$ and $T_2$, and $P_c$ is the power per unit area flowing between the two points due to thermal conduction. Different materials can have widely varying values for $K$, as we see in Table 3.

The materials listed in the table are building materials (except water and air, which are listed for comparison). The values in the second column represent the power conducted through 1 square meter of the material that is 1 cm thick when the temperature drop across the 1 cm is 1 °C. For example, a 1-cm thickness of gypsum board will conduct 40 watts/m² when there is a temperature drop of 1 °C across the gypsum board.

A more important example concerns a 2-mm thickness of windowpane glass with a 1-m area. When the temperature drop across the glass is 20 °C (or 36 °F, 32 °F outside and 68 °F inside), the heat loss is 8,000 watts per window; this corresponds to 80 light bulbs at 100 watts each for every window in the house. Most people would never deliberately turn on that many lights and waste that much energy, but those same people do not replace their windows or...
otherwise minimize the heat losses from their homes or businesses.

The third column compares the heat-stopping power or insulating capability of the various materials compared to one unit thickness of fiberglass insulation. For example, we see from the table that a brick wall 15 inches thick has the equivalent insulating properties of 1-inch-thick fiberglass. We would require 5,000 inches of aluminum to insulate as well. Materials that are good electrical conductors are also good heat conductors, because of all of the loose electrons capable of moving around in the material.

If we heat a parcel of a fluid that is surrounded by a cooler parcel of the same fluid, the warmer fluid expands and becomes less dense. The more dense adjacent fluid will move underneath the less dense parcel and displace it upward. (Hot air rises because the cooler air pushes it upward.) The combined motion of warmer fluid moving upward and cooler fluid moving downward produces an upward flow of thermal energy that we call convection.

Convection is a process that involves complex turbulent motions in the fluid and cannot easily be described mathematically. We do know that convection is much more efficient than conduction in fluids; therefore convection is always present in fluids when differential heating or cooling occurs. The convection processes, rather than conduction, transfer thermal energy in fluids except at boundaries with solids, where once again conduction dominates. The purpose of fibrous insulation materials, such as fiberglass and cellulose, used above ceilings and in walls, is to prevent convection from occurring. These insulating materials produce so much friction on the motion of the air that convection cannot occur.

Convection is a process similar to convection, in which the fluid is forced to move by winds, pumps, or fans, predominantly in the horizontal. When you stir a pot of soup, turn on a ceiling fan, or open a window to let the breeze in, it is advection that is moving the thermal energy.

Thermal energy can also be transferred by radiation processes; thermal radiation, $P_T$, is a sensitive function of temperature, $T$,

$$P_T = \sigma T^4 \quad (12)$$

where the Stefan-Boltzmann constant, $\sigma$, is

$$\sigma = 5.67 \times 10^{-8} \text{ W/m}^2/\text{K}^4 \quad (13)$$

$P_T$ is radiated power in watts per square meter, and the temperature must be expressed in Kelvins or absolute temperature. Thermal radiation is another form of electromagnetic radiation that we discussed earlier. Equation 12 goes by the strange name of “the blackbody radiation law”; most solid and liquid surfaces at normal temperatures will produce thermal radiation according to this law. Blackbody radiation occurs when the atoms and molecules in a substance are closely packed so that they are continuously interacting and some electrons are loosely shared. When the atoms and molecules are widely separated and independent, as in a gas, they cannot collectively radiate as a blackbody but can only exchange radiation at specific wavelengths determined by changes in the energy levels of their atomic and molecular structure.

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Power Conducted W/m²</th>
<th>Equivalent Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>20,000</td>
<td>5,000</td>
</tr>
<tr>
<td>Concrete</td>
<td>100</td>
<td>25</td>
</tr>
<tr>
<td>Glass</td>
<td>80</td>
<td>20</td>
</tr>
<tr>
<td>Brick</td>
<td>60</td>
<td>15</td>
</tr>
<tr>
<td>Water</td>
<td>60</td>
<td>15</td>
</tr>
<tr>
<td>Gypsum</td>
<td>40</td>
<td>10</td>
</tr>
<tr>
<td>Cinder block</td>
<td>30</td>
<td>8</td>
</tr>
<tr>
<td>Wood (variable)</td>
<td>10</td>
<td>2.5</td>
</tr>
<tr>
<td>Fiber glass</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Air (nonconvective)</td>
<td>2.5</td>
<td>0.6</td>
</tr>
</tbody>
</table>
The energy-level changes in the diatomic molecules, nitrogen and oxygen, that make up 99% of our atmosphere are too large to absorb or emit radiation in the visible or infrared regions of the electromagnetic spectrum; because of this our atmosphere is mostly transparent to solar radiation. On the other hand, the triatomic and larger molecules, water, carbon dioxide, methane, ozone, etc., have lower energy-level changes that allow them to absorb and emit electromagnetic radiation in the visible and infrared; these are the “greenhouse” gases. Without the greenhouse gases earth would be a frozen wasteland; too much and earth may become too warm.

It is not chance that we see in the visible part of the spectrum; it was an evolutionary necessity that our vision work in the transparent part of the atmosphere.

Another important characteristic of blackbody radiation is that the temperature of the radiating material determines where in the electromagnetic spectrum most of the energy is radiated. This peak in the radiation spectrum occurs at the wavelength, \( \lambda \) (in \( \mu \)m), given by Wien’s Law

\[
\lambda = \frac{2898}{T}
\]  

(14)

where \( T \) must be in Kelvin or absolute. This equation tells us that the hotter the material the shorter the wavelength of the peak power. Table 4 will give you a feeling for the range of thermal radiation that we normally encounter.

The wavelength range for visible light goes from red at 0.7 \( \mu \)m to violet at 0.4 \( \mu \)m, which is not very wide. Of the thermal radiating objects in the table, only the sun has a peak in the visible range. The incandescent or tungsten light bulb (at 3,200 K) produces a yellowish-white light, and color photographs using this light do not reproduce true colors. Even though it appears nearly white, most of the power used by the light bulb is going into infrared radiation and heat. Only 2% to 5% of the electrical energy used by the light bulb produces visible light—light bulbs are notoriously inefficient. All systems that depend upon thermal radiation to produce visible light will be inefficient, because visible light is a narrow spectral range and thermal radiation is very broad. Fluorescent lights can achieve efficiencies in the 10% to 12% range, which is not very good but far better than the incandescent light bulb. Fluorescent lights do not use thermal radiation; they have a chemical coating on the inside of the tube that “fluoresces” when excited by the plasma discharge in the gas inside the tube. To explore how different lights work, go to http://www.sylvania.com/cool/welcome.htm on the World Wide Web.

The flame temperatures for methane (natural gas) and gasoline are shown in the Table 4. Clean-burning flames do not produce blackbody radiation because they are gases. The yellow flames that we see in wood fires and candles are hot particles of incomplete combustion products. When you extinguish a candle you will see these particles rising above the candle as smoke.

In many situations, all four of the thermal transfer processes (conduction, convection, advection, and radiation) will be working simultaneously. Your room may have a forced air heating and cooling system that moves air into and out of the room by advection. The walls, floor, and ceiling are radiating thermal energy trying to keep everything at the same temperature. At the window, heat is being conducted through the glass, and at both glass surfaces heat is conducted to or from the adjacent air. The air adjacent to the glass will sink if cooled or rise if warmed; in both cases convection is moving the thermal energy around. There are so many processes that transfer thermal energy that it is no wonder that thermal systems tend to be inefficient. The good news is that we know how to deal with these inefficiencies, and if motivated we can achieve great energy savings.

Our heat conduction equation (11) displays fundamental and important behavioral information about thermal systems; the heat you move is proportional to the temperature
difference. The final process of transferring heat energy involves transfer to the environment at $T_E$. There is another relationship for the efficiency of a heat engine that is equally important, the Carnot Cycle.

If we were to imagine an absolutely perfect engine that converted heat energy at $T_H$ to mechanical energy, we would find that the efficiency of the engine would be given by the Carnot equation:

$$E = \frac{(T_H - T_E)}{T_H} \quad (15)$$

We see once again that it is the difference in temperature, in this case between the source and the environment, that limits performance.

For an example, let’s start with a simple steam engine ($T_H = 373 \text{ K} = 100 \text{ °C}$) in an environment of $T_E = 303 \text{ K} = 30 \text{ °C} (= 86 \text{ °F})$. The efficiency of the perfect engine operating at these temperatures is

$$E = \frac{(373 - 303)}{373} = 19\%$$

Real steam engines increase efficiency by using steam under high pressure, which has a higher temperature, but in practice they are also faced with higher exit or environmental temperatures.

To appreciate the difference between the exit temperature and the environmental temperature we can split the steam engine into two parts. The first part transforms the heat energy into mechanical energy, and the second part moves the waste heat from the engine into the environment; this latter part is the required waste power discussed in the previous section, and the engine will not run if the second part of the engine cannot perform this essential function. If the steam engine is approximately 20% efficient, then the second part, the cooling part of the engine, must handle 80% of the input energy. There are three temperatures that must be considered: $T_H$, $T_E$, and $T_f$, the exit temperature of the first part of the engine and the input temperature to the cooling part of the engine. In order to move large quantities of waste
power through the cooling section, $T_e$ must be greater than $T_e'$, but increasing $T_e'$ necessarily decreases the efficiency of the first part of the engine, which is the part that produces the mechanical power of the engine.

The best efficiency ever produced by classical (reciprocating) steam engines was 25%, but this was with large and heavy engines because the steam pressure had to be increased by 100 times to achieve this efficiency. The classical steam engine has been replaced by steam turbine engines that are much lighter. A steam turbine with an input temperature of 600 °C can operate with an efficiency of approximately 40%.

**Energy Quality**

In this section we want to introduce you to an important concept that describes the quality of energy. A 12-volt automotive battery, fully charged, can store roughly $3 \times 10^6$ J of energy. By comparison, a lecture hall (6 m × 8 m × 4 m) in which the air temperature has been warmed by 10 °C relative to the environment has the same amount of energy.

The automotive battery may be used to
1. produce mechanical energy in a starter, winch, fan, or other electrical motor;
2. produce light when connected to an automotive lamp;
3. produce and receive electromagnetic radiation when connected to a radio transmitter or receiver or cellular telephone;
4. produce acoustic power (sometimes too much) when connected to an amplifier and loudspeakers; and
5. heat the lecture hall by 10 °C, when connected to a heater.

Now, what kind of energy transformations are available to the warm room? Only one: when you open the door, a convective current will be produced that allows the cooler outside air to enter the lower level of the room and pushes the warmer air out the door. You can never charge the battery using the warm air.

Although the quantity of the energy is the same in these two examples, the form or quality of the energy is very different. It is this difference in quality that we wish to explore.

We find the explanation for the quality of energy in the science of thermodynamics, which literally means heat energy dynamics. The First Law of Thermodynamics says that energy is conserved in a closed system. We have used this law many times in this book already: you can transform energy or move it, but you cannot create it or destroy it. The Second Law of Thermodynamics is just as important but more subtle because it involves an understanding of entropy, which we will now explore.

Entropy measures how broadly the energy in a system is distributed—in other words, how much disorder there is in the system. In our previous example the warm room distributed its energy among all of the molecules of gas in the room; the system was highly disordered. The battery, however, had all of its energy highly concentrated in the chemical compounds attached to its plates; the system was highly ordered. Even though the energy is the same, the warm room has higher entropy than the battery. The quality of the energy in the battery is much higher from the human perspective because it is easily transformed into useful forms; we therefore associate high quality with low entropy.

The Second Law of Thermodynamics says that entropy is always increasing in closed systems. That’s a bummer! The first law says that we can never get any new energy, and the second law says that the energy that we have is continuously getting less useful. Physicists sometimes refer to this process as the heat death of the universe. These two laws should make us all more conscientious users of energy even if there were no energy crisis.

We have already seen several consequences of the second law. The law of thermal conduction given in Equation 11 says that energy only flows from the warmer object to the cooler object, and furthermore, that the rate of energy
flow is proportional to the temperature difference. This is a consequence of the second law, because the heat transfer process distributes the energy more broadly: entropy increases. The Carnot equation (15) is very similar; you cannot create an efficient engine with small temperature differences—or, stated differently, if you design your engine to work with nature, it will be more efficient.

For thermal systems there is a rather simple expression for the change in entropy, dS, that occurs in a system when a quantity of thermal energy, dQ, is added to the system:

\[ dS = \frac{dQ}{T} \quad (16) \]

where T is the temperature associated with the energy being transformed. This entropy equation demonstrates the close connection that entropy has to temperature; for the same quantity of energy (dQ) the entropy is smaller for higher temperature. Since energy quality is associated with low entropy, we can associate high temperature with high quality with respect to energy transformations. (This is only a small part of the story of entropy. We have left out many other important considerations, such as phase transformations, but the simple result used here is very powerful.)

We can extend the concepts of these laws of thermodynamics to include other forms of energy. In the case of electromagnetic energy we can use Wien’s Law (14) to relate the wavelength of electromagnetic radiation to a temperature. See the examples in Table 5.

For electrical energy we convert the energy gained by an electron accelerated in a vacuum through one volt and use an equation like Equation 7 to associate a temperature with a volt. We find that one volt is roughly equivalent to 10,000 K; the energy gained by the electron is equivalent to a molecule of gas heated to 10,000 K. Recall that the electrical force is a strong force, and also recognize that a small flashlight at 1.5 volts can produce nearly white light by the very inefficient process of incandescent light. The electrical examples in Table 5 all have high associated temperatures.

In Table 5 the “Quality Temperature” is a scale based on energy comparison that is useful in applying thermodynamic concepts across the broad range of human energy use. Our earlier example of the car battery and the warm lecture room can now be viewed with a quality temperature approach. The car battery has a quality temperature of 120,000 K, while the room temperature is only 300 K (−86 °F). It is easy to see how the battery can produce light at 3,200 K and follow the Second Law of Thermodynamics, which requires energy to flow from the higher to the lower temperature, but the warm room cannot produce light (or any of the other manifestations listed) because its temperature is only 300 K.

Equation 15 gives the efficiency for the perfect engine, which we have seen for steam turbines is less than 45%. Electric motors can be produced to operate close to 100% efficiency because the input or quality temperature is over 100,000 K.

<table>
<thead>
<tr>
<th>Energy Type</th>
<th>Quality Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visible light</td>
<td>5,800, the surface temperature of the sun</td>
</tr>
<tr>
<td>Earth infrared</td>
<td>288, the average earth temperature</td>
</tr>
<tr>
<td>Solar ultraviolet</td>
<td>10,000, the source of sunburn</td>
</tr>
<tr>
<td>Gamma rays produced in nuclear disintegrations</td>
<td>50 billion represents the very strong nuclear force</td>
</tr>
<tr>
<td>Flashlight with two batteries (3V)</td>
<td>30,000 represents the strong electrical force</td>
</tr>
<tr>
<td>Household electricity (120 V)</td>
<td>1.2 million; small wires can be explosively vaporized with household electricity</td>
</tr>
<tr>
<td>Gasoline burning in air</td>
<td>2,500, the maximum</td>
</tr>
</tbody>
</table>