Section 2

Energy Fundamentals
Energy Fundamentals

- Open and Closed Systems
- First Law of Thermodynamics
- Second Law of Thermodynamics
  - Examples of heat engines and efficiency
- Heat Transfer
  - Conduction, Convection, Radiation
- Radiation and Blackbodies
  - Electromagnetic Radiation
  - Wien’s Law, Stefan-Boltzmann Law
Energy Fundamentals

• To analyze energy flows,
  → Define type of system
  → Use 1st and 2nd Laws of Thermodynamics

Open System: energy or matter flow across boundaries
Closed System: only energy flows across boundaries
First Law of Thermodynamics

• “Energy cannot be created or destroyed”

• Energy balance equation:
  Energy in = Energy out + Change in internal energy

→ Change in internal energy $\Delta U$ commonly due to change in temperature:
  $$\Delta U = mc\Delta T$$

$m$ = mass
$c$ = specific heat
$\Delta T$ = temperature change
Units of specific heat \( c \) (definitions):

\[
\begin{align*}
\text{Energy} &= \frac{\text{Unit mass \times Temperature}}{} \\
1 \text{ BTU} &\text{ is the energy required to raise the temperature of 1 lb of water by 1°F.} \\
1 \text{ calorie} &\text{ is the energy required to raise the temperature of 1 gram of water by 1°C.} \\
1 \text{ kilojoule} &\text{ (preferred)}
\end{align*}
\]

For water,

\[
c = 1 \frac{\text{cal}}{\text{g} \cdot \°\text{C}} = 4.184 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}
\]
<table>
<thead>
<tr>
<th>Substance</th>
<th>(kJ/kg °C)</th>
<th>(kcal/kg °C, Btu/lb °F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water (15 °C)</td>
<td>4.18</td>
<td>1.00</td>
</tr>
<tr>
<td>Air (20 °C)</td>
<td>1.01</td>
<td>0.24</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.92</td>
<td>0.22</td>
</tr>
<tr>
<td>Copper</td>
<td>0.39</td>
<td>0.09</td>
</tr>
<tr>
<td>Dry soil</td>
<td>0.84</td>
<td>0.20</td>
</tr>
<tr>
<td>Ice</td>
<td>2.09</td>
<td>0.50</td>
</tr>
<tr>
<td>Steam (100 °C)(^{a})</td>
<td>2.01</td>
<td>0.48</td>
</tr>
<tr>
<td>Water vapor (20 °C)(^{a})</td>
<td>1.88</td>
<td>0.45</td>
</tr>
</tbody>
</table>

\(^{a}\)Constant pressure values.
When a substance changes phase by freezing or boiling,

\[ \Delta U = mH_L \]

\( H_L \) = latent heat

\( m \) is the mass of substance

Internal energy changes due to phase changes:

Changing from solid → liquid:

*Latent Heat of Fusion*

Changing from liquid → gas:

*Latent Heat of Vaporization*

\( H_L \) (fusion of 0°C water) = 333 kJ/kg
\( H_L \) (vaporization of 100°C H₂O) = 2257 kJ/kg
Heat needed to convert 1 kg of ice to steam. To change the temperature of 1 kg of ice, 2.1 kJ/°C needed. To completely melt that ice requires another 333 kJ (latent heat of fusion). Raising the temperature of liquid water requires 4.184 kJ/°C, and converting it to steam requires another 2257 kJ (latent heat of vaporization). To raise the temperature of 1 kg of steam (at atmospheric pressure) requires another 2.0 kJ/°C.
Example: Global Precipitation

Over entire globe (area of globe $5.1 \times 10^{14} \text{ m}^2$), precipitation averages 1 m/yr.
What energy is required to evaporate all of the precipitation if the temperature of the water is 15 °C?

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Specific heat (15°C)</td>
<td>4.184 kJ/kg</td>
</tr>
<tr>
<td>Heat of Vaporization</td>
<td></td>
</tr>
<tr>
<td>(100°C)</td>
<td>2257 kJ/kg</td>
</tr>
<tr>
<td>Heat of Vaporization</td>
<td></td>
</tr>
<tr>
<td>(15°C)</td>
<td>2465 kJ/kg</td>
</tr>
<tr>
<td>Heat of Fusion</td>
<td>333 kJ/kg</td>
</tr>
</tbody>
</table>
Use First Law of Thermodynamics:

Energy = Energy + Change in
In   Out   Internal Energy

In this case, assume “energy out” = 0 (no losses, and all energy put into the system is used for evaporation)

⇒ Energy In = Change in Internal Energy
   = \( mH_L \)
\[ m = (1 \text{m/yr})(5.1 \times 10^{14} \text{ m}^2)(1000 \text{ kg/m}^3) \]
\[ = 5.1 \times 10^{17} \text{ kg/yr} \]

Energy = \((5.1 \times 10^{17} \text{ kg/yr})(2465 \text{ kJ/kg})\)
\[ = 1.3 \times 10^{21} \text{ kJ/yr} \]

**IMPORTANT:** use the latent heat for water at 15°C, not 100°C

This is \( \sim 4000 \) times larger than world energy consumption!

(Global fossil fuel consumption is about \(3.5 \times 10^{17} \text{ kJ/yr}\))
Example: An Open System

Many practical situations exist where both mass and energy flow across boundaries: heat exchangers, cooling water, flowing rivers.

Rate of change in stored energy (due to flow)

\[ \dot{m} c \Delta T \]

where \( \dot{m} \) is the mass flow rate across boundaries of the system of interest.
A coal-fired powerplant converts one-third of the coal’s energy into electricity, with an electrical output rate of 1000 MW (1 MW = 10^6 J/s)

The other 2/3 goes back into the environment: 15% to the atmosphere, up the stack 85% into a nearby river

The river flows at 100 m^3/s and is 20°C upstream of the plant

If the stream of water that is put back into the river is to be at no more than 30°C, how much water needs to be drawn from the river?
Amount of waste heat going into the river:

\[ 2000 \text{ MW} \times 85\% = 1700 \text{ MW} \]
\[ = 1700 \times 10^6 \frac{\text{J}}{\text{s}} = 1.700 \times 10^9 \frac{\text{J}}{\text{s}} \]

Rate of change in stored energy due to flow

\[ = \dot{m}c\Delta T \]
\[ \dot{m}(\text{kg/s}) = \frac{\text{waste heat}}{c\Delta T} \]
\[ = \frac{1.700 \times 10^9 \frac{\text{J}}{\text{s}}}{4184 \frac{\text{J}}{\text{kg K}} \times 10 \text{ K}} = 4.063 \times 10^4 \frac{\text{kg}}{\text{s}} \]
Second Law of Thermodynamics

• “The entropy of a system tends to increase.”

• Entropy is a measure of disorganization in a system

  → Thermal energy not available for conversion into mechanical work

  → Conversion of heat to work results in some waste heat—a heat engine cannot be 100% efficient
• A coal-fired powerplant is a type of heat engine

→ Burn coal for heat

→ Boil water to make steam

→ Steam turns turbine—some of heat in steam converted to electricity

→ Exiting steam is at a lower temperature—waste heat

— Co-generation?
Heat Engine

Hot reservoir $T_h$

$Q_h$ Heat to engine

$Q_c$ Waste heat

Cold reservoir $T_c$

Efficiency $\equiv \frac{\text{work}}{\text{heat input}} = \frac{W}{Q_h} = \eta$
• Theoretically, the most efficient heat engine is the Carnot Engine:

For Carnot, \[ \eta = 1 - \frac{T_c}{T_h} \]

\( T_c, T_h = \) absolute temperature, in K or R

\( c = \) cold, \( h = \) hot, \( \eta = \) efficiency

• As \( T_h \) increases \( \eta \) increases; as \( T_c \) decreases, \( \eta \) increases

⇒ The larger the difference in temperature, the more efficient the process
Typical Powerplant

Energy output = 1000 MW
Pressurized steam boiler = 600°C = 873 K
Cooled to ambient temperature = 20°C = 293 K

\[ \eta_{\text{max}} = 1 - \frac{293}{873} = 0.66 = 66\% \]

Real-world efficiencies in U.S. powerplants average 33% (range ~ 25 to 40% depending on age of plant)
Some conversions

Kilowatt-hour
(KWH or kW-hr)

1 W = 1 J/s  ⇒  1 J = 1 W • s

1 Watt-hour = 1 W • 3600 s = 3600 J

1 kW-hr = 1000 • 1 W • 3600 s = 3.6 × 10^6 J = 3.6 MJ
A 15W compact fluorescent lamp (CFL) provides the same light as a 60W incandescent lamp. Electricity costs the end user 10¢ per kW-hr.

a. If an incandescent lamp costs 60¢ and the CFL costs $2, what is the “payback” period?

b. Over the 9000-hr lifetime, what would be saved in carbon emissions? (280 g carbon emitted per kW-hr)

c. At a (proposed) carbon tax of $50/tonne, what is the equivalent dollars saved as carbon emissions? (1 tonne = 1000 kg)
Energy saved with the CFL:

\[(60W - 15W)(9000 \text{ hr}) = 405 \text{ kW-hr}\]

At 10¢ per kW-hr, this is $40 over the lifetime of the lamp.

Payback period: As an example, use 6 hr/day usage.

Then

\[
\frac{(60W - 15W)(6 \frac{\text{hr}}{\text{day}})(0.10 \frac{1}{\text{kW-hr}})}{1000 \frac{\text{W-hr}}{\text{kW-hr}}}
\]

\[= \$0.027 \text{ saved per day}\]

$2/$0.027 per day = 74 days or about 2.5 months

Emissions savings:

\[(280 \text{ g carbon/kW-hr})(405 \text{ kW-hr}) = 113400 \text{ g C}\]

\[\Rightarrow 0.113 \text{ T} \times \$50/\text{T} = \$5.65\]
Example

Could the temperature difference between the top and bottom of a lake be used as a cheap, renewable source of a megawatt of electricity?

Say the temperatures are 25°C and 15°C, maintained by sunlight (~ 500 W/m²) and the lake has an area of $10^4$ m².

Are the first and second laws of thermodynamics obeyed? [first: energy is conserved; second: entropy of systems increase and there is a limit on the efficiency of any process]
Evaluate maximum efficiency, then calculate energy output

\[ \eta = 1 - \frac{T_c}{T_h} \]

\[ \eta_{\text{max}} = 1 - \frac{288}{298} = 0.034 \]

What is the maximum possible energy output from this system, given the solar energy input?

\[ \left(500 \frac{W}{m^2}\right) \left(10^4 \text{ m}^2\right) \left(0.034\right) = 170000 \text{ W} = 0.17 \text{ MW} \]
A very efficient gasoline engine runs at 30% efficiency. If the engine expels gas into the atmosphere, which has a temperature of 300 K, what is the temperature of the cylinder immediately after combustion?

If 837 J of energy are absorbed from the hot reservoir during each cycle, how much energy is available for work?

\[
\eta = 1 - \frac{T_c}{T_h}
\]

\[
\eta = \frac{W}{Q_h}
\]
Heat Transfer

- Heat transfer always occurs between hot and cold objects

→ Conduction: heat transfer occurs when there is direct physical contact; kinetic energy is transferred when atoms or molecules collide
→ Convection: heat transfer is mediated by the flow of a fluid

- Free convection occurs without human intervention; forced convection requires mechanical pumping of the fluid

→ Radiation: heat transfer mediated by the propagation of electromagnetic radiation (such as light)
Radiation

- All objects radiate energy continuously in the form of electromagnetic waves, if their temperature is greater than 0 K

- Type of radiation depends on wavelength
Blackbody Radiation

- Blackbodies absorb and emit at all wavelengths
- Amount of radiation emitted depends on temperature

Stefan-Boltzmann Law

\[ E = \sigma AT^4 \]

- \( E \) = total blackbody emission rate (W)
- \( \sigma \) = Stefan-Boltzmann constant = \( 5.67 \times 10^{-8} \) W/m\(^2\)K\(^4\)
- \( T \) = temperature (K)
- \( A \) = surface area of blackbody (m\(^2\))
A more familiar form uses the energy flux $F$, where $F = \frac{E}{A} \text{W/m}^2$

$$F = \sigma T^4$$

Wien’s Law

$$\lambda_{\text{max}} (\mu\text{m}) = \frac{2898 \mu\text{m} \cdot \text{K}}{T \ (\text{K})}$$
Example: Human Body as an Energy Converter

How high can you climb on the energy from a liter of milk?

One liter of milk contains about $2.4 \times 10^6$ J.

$$ (2.4 \times 10^6 \text{ J}) \times \left( \frac{1 \text{ kJ}}{1000 \text{ J}} \right) \times \left( \frac{1 \text{ cal}}{4.184 \text{ kJ}} \right) = 574 \text{ cal} $$

Work needed to move your body = $mgh$

where $m =$ your mass, $g =$ acceleration due to gravity, $h =$ change in height
Work available from milk

\[ = (\text{metabolic efficiency})Q = \varepsilon Q \]

where \( Q \) is the internal energy of the milk

Example input values: \( m = 50 \text{ kg (110 lb)}, \) efficiency \( \sim 100\% \)

\[ \varepsilon Q = mgh \]

\[ (1.0)(2.4 \times 10^6 \text{ J}) = (50 \text{ kg})(9.8 \text{ m/s}^2)h \]

\[ h = 4900 \text{ m} \]

Considering that Mt. Whitney has an elevation gain of about 3000 m, does this sound reasonable?