L 19 - Thermodynamics [4]

- Heat capacity
- Change of phase (ice $\rightarrow$ water $\rightarrow$ steam)
- heat, work, and internal energy
- the 1st Law of Thermodynamics
- THE 2nd Law of Thermodynamics

How do I boil water?

- How much heat does it take to boil water, i.e., how much heat must be transferred to a specific mass of water to raise its temperature to the boiling point?
- Related question: How much heat is required to raise the temperature of water by a specified number of degrees?
- The answer depends on how much water you have and how hot you want to get it $\rightarrow$ m and $\Delta T$, where m is the mass and $\Delta T$ is the temperature change.
- The answer would be different for a different material, say aluminum $\rightarrow$ there must be a parameter for each substance – heat capacity, c.

Examples- heat capacity

(1) How much heat must be added to 1 kg of water to increase its temp from 20°C to 60°C?
$Q = mc\Delta T = 1000g \times 1\text{cal/g}^\circ\text{C} \times 40^\circ\text{C} = 40,000\text{C}$

(2) How much heat must be removed from 2 kg of water to cool it from 90°C to 10°C?
$Q = mc\Delta T = 2000g \times 1\text{cal/g}^\circ\text{C} \times -80^\circ\text{C} = 160,000\text{C}$

How much water you have and how hot you want to get it $\rightarrow$ m and $\Delta T$, where m is the mass and $\Delta T$ is the temperature change.

Some heat capacities

<table>
<thead>
<tr>
<th>Substance</th>
<th>Specific heat in cal/g °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>water</td>
<td>1</td>
</tr>
<tr>
<td>Ethyl alcohol</td>
<td>0.58</td>
</tr>
<tr>
<td>Steel</td>
<td>0.11</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.215</td>
</tr>
<tr>
<td>lead</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Heat Capacity or specific heat

- The heat capacity is the amount of heat that is required to raise the temperature of 1 g of a substance by 1 degree C.
- It is measured in **Calories**.
- For water it is 1 cal/g °C.
- $Q = m \times c \times \Delta T$.

Examples of phase change:

<table>
<thead>
<tr>
<th>Temperature in °C</th>
<th>Heat added</th>
</tr>
</thead>
<tbody>
<tr>
<td>-20°C</td>
<td>ice</td>
</tr>
<tr>
<td>0°C</td>
<td>melt ice</td>
</tr>
<tr>
<td>100°C</td>
<td>boil water</td>
</tr>
<tr>
<td>100°C</td>
<td>steam</td>
</tr>
</tbody>
</table>

Temperature change is always positive.
Temperature is not the whole story!
- some recipes have high altitude instructions
- The temperature at which water boils is 212°F at sea level.
- At higher altitudes, where the pressure is lower, water boils at a lower temperature:
  - at 5000 ft it boils at 203°F
  - at 7200 ft it boils at 199°F
- If we increase the pressure above atmospheric pressure, water is harder to boil.

You can boil with ice!
- As the water boils, the pressure builds up.
- By cooling the water vapor, the water can be made to boil.

Energy from natural gas
- 1 BTU = the heat needed to raise the temperature of 1 pound of water by 1°F
- 1 cubic foot of natural gas provides about 1000 BTU when burned.
- So to boil (go from 72°F to 212°F) one gallon of water (about 8 lbs) requires about 1 BTU/°F * 140 °F = 140 BTU/lb.
  x 8 lbs → 1120 BTU’s or more than 1 ft³.
- 1 cubic foot of natural gas costs about 1.5¢; it would cost about 3¢ using electricity.

Boiling water
- Energy is required to remove molecules from a liquid.
- The buildup of pressure inhibits molecules from leaving the liquid.
- A pressure cooker cooks food at a temp above the boiling point.

Making ice in a vacuum
Freeze drying
- PUMP
- BELL JAR

Heat, work, and internal energy
- The gas has internal energy, as indicated by its temperature.
- If heat is added, its internal energy increases.
- If the gas expands and does work on the atmosphere, its internal energy decreases.
- The 1st law of thermodynamics keeps track of the balance between the heat, work and internal energy of the gas.
The first law of thermodynamics

• The change in internal energy of the gas
  \[
  \text{heat absorbed by the gas} - \text{work done by the gas}
  \]
• This is a simple energy accounting principle

Analogy to your bank account

• The change in your bank account balance
  \[
  \text{deposits ($ in)} - \text{withdrawals ($ out)}
  \]
• The same conservation principle applies to energy transfers

**1st Law of Thermodynamics**

<table>
<thead>
<tr>
<th>Change in internal energy</th>
<th>HEAT</th>
<th>WORK</th>
</tr>
</thead>
<tbody>
<tr>
<td>increase</td>
<td>in</td>
<td>0</td>
</tr>
<tr>
<td>increase</td>
<td>0</td>
<td>on gas</td>
</tr>
<tr>
<td>decrease</td>
<td>out</td>
<td>0</td>
</tr>
<tr>
<td>decrease</td>
<td>0</td>
<td>by gas</td>
</tr>
<tr>
<td>increase</td>
<td>in</td>
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</tr>
<tr>
<td>decrease</td>
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<td>by gas</td>
</tr>
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</table>

*all quantities measured in Joules or Calories*

WORK \ HEAT

CHANGE IN INTERNAL ENERGY

EXAMPLE

• What is the change in the internal energy of a gas if 3000 J of heat are added while the gas does 1000 J of work?
• Change in internal energy
  \[
  \text{heat in} - \text{work done} = 3000 \text{ J} - 1000 \text{ J} = 2000 \text{ J}
  \]

Heat engines

• A heat engine is a device that uses heat (input, which you must pay for in some form) to do work (output which is useful).
• A central issue is how much of the heat taken in can be converted into work
• The outcome is first of all limited by the 1st law (you can’t get more out than goes in)
heat engine operate in a cycle

work can be used to run an electric generator or turn the shaft of a propeller

Second law of thermodynamics

<table>
<thead>
<tr>
<th>HEAT is random energy</th>
<th>WORK is ordered energy</th>
</tr>
</thead>
</table>

I. (*Kelvin*) It is impossible to have a heat engine that is 100% efficient
   ➔ Not all of the heat taken in by the engine can be converted to work

II. (*Clausius*) In a spontaneous process, heat flows from a hot to a cold substance
   ➔ Work must be done to move heat from a cold to a hot substance.