Chapter 5: Temperature and Heat

Homework: All questions on the “Multiple-Choice” and the odd-numbered questions on “Exercises” sections at the end of the chapter.

Temperature

- “Hot” & “Cold” are relative terms.
- Temperature depends on the kinetic (motion) energy of the molecules of a substance.
- Temperature is a measure of the average kinetic energy of the molecules of a substance.

Thermometer

- Thermometer - an instrument that utilizes the physical properties of materials for the purpose of accurately determining temperature.
- Thermal expansion is the physical property most commonly used to measure temperature.
  - Expansion/contraction of metal
  - Expansion/contraction of mercury or alcohol

Bimetallic Strip and Thermal Expansion

- Brass expands more than iron.
- The degree of deflection is proportional to the temperature.
- A/C thermostat and dial-type thermometers are based on bimetal coils.

Liquid-in-glass Thermometer

- Thermometers are calibrated to two reference points (ice point & steam point.)
  - Ice point – the temperature of a mixture of pure ice and water at normal atmospheric pressure
  - Steam point – the temperature at which pure water boils at normal atmospheric pressure
- Usually contains either mercury or red (colored) alcohol

Temperature Scales

Celsius, Kelvin, Fahrenheit

Steam point (water boil): 100 °C, 373 K, 212 °F
Normal body temperature: 37 °C, 98.6 °F
Boiling temperature (water freeze): 0 °C, 32 °F
Ice point: 0 °C, 273 K, 32 °F
Absolute zero: -273 °C, 0 K, -460 °F
Temperature Scales
Celsius, Kelvin, Fahrenheit

<table>
<thead>
<tr>
<th>Scale</th>
<th>Absolute Zero</th>
<th>Ice Point</th>
<th>Steam Point</th>
<th>Diff. (Boil – Ice)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fahrenheit</td>
<td>-460°</td>
<td>32°</td>
<td>212°</td>
<td>180</td>
</tr>
<tr>
<td>Celsius</td>
<td>-273°</td>
<td>0°</td>
<td>100°</td>
<td>100</td>
</tr>
<tr>
<td>Kelvin</td>
<td>0°</td>
<td>273°</td>
<td>373°</td>
<td>100</td>
</tr>
</tbody>
</table>

Converting Temperatures is Easy!
- \( T_K = T_C + 273 \) (Celsius to Kelvin)
- \( T_C = T_K - 273 \) (Kelvin to Celsius)
- \( T_F = 1.8 T_C + 32 \) (Celsius to Fahrenheit)
- \( T_C = \frac{T_F - 32}{1.8} \) (Fahrenheit to Celsius)

Converting a Temperature - Example
- The normal human body temperature is usually 98.6°F. Convert this to Celsius.
- EQUATION: \( T_C = \frac{T_F - 32}{1.8} \)
  - \( T_C = \frac{98.6 - 32}{1.8} = \frac{66.6}{1.8} = 37.0°\text{C} \)

Converting a Temperature
Confidence Exercise
- Convert the Celsius temperature of -40°C into Fahrenheit.
- EQUATION: \( T_F = 1.8 T_C + 32 \)
  - \( T_F = 1.8(-40) + 32 = -72 + 32 = -40°\text{F} \)
  - -40°C is the same for either Celsius or Fahrenheit!

Heat
- Kinetic and Potential energy both exist at the molecular level.
  - Kinetic – motion of molecules
  - Potential – bonds that result in the molecules oscillating back and forth
- Heat is energy that is transferred from one object to another as a result of a temperature difference.
- Heat is energy in transit because of a temperature difference.

Heat Unit SI - Calorie
- Since heat is energy, it has a unit of joules (J)
- A more common unit to measure heat is the calorie.
  - Calorie – the amount of heat necessary to raise one gram of pure water by one Celsius degree at normal atmospheric pressure
  - 1 cal = 4.186 J (or about 4.2 J)
- Kilocalorie – heat necessary to raise 1kg water by 1°C
  - 1 food Calorie = 1000 calories (1 kcal)
  - 1 food Calorie = 4186 J (or about 4.2 kJ)
Heat Unit British - Btu

- British thermal unit (Btu) – the amount of heat to raise one pound of water 1°F
- 1 Btu = 1055 J = 0.25 kcal = 0.00029kWh
- A/C units are generally rated in the number of Btu’s removed per hour.
- Heating units are generally rated in the number of Btu’s supplied per hour.

Expansion/Contraction with Δ’s in Temperature

- In general, most matter, solids, liquids, and gases will expand with an increase in temperature (and contract with a decrease in temperature.)
- Water is an exception to this rule – (ice floats!)

Thermal-Expansion Joints in a Bridge

These joints allow for the contraction and expansion of the steel girders during the winter and summer seasons.

Behavior of Water \( \rightarrow \) Strange!

- The volume of a quantity of water decreases with decreasing temperature but only down to 4°C. Below this temperature, the volume increases slightly.
- With a minimum volume at 4°C, the density of water is maximum at this temperature and decreases at lower temperatures.

Behavior of Water: Structure of Ice

- Solid water takes up more volume

  a) An illustration of the open hexagonal (six-sided) molecular structure of ice.
  b) This hexagonal pattern is evident in snowflakes.

Yellowstone Lake - Frozen
Specific Heat (Capacity)

- If equal quantities of heat are added to equal masses of two metals (iron and aluminum, for example) – would the temperature of each rise the same number of degrees? -- NO!
- Different substances have different properties.
- Specific Heat – the amount of heat necessary to raise the temperature of one kilogram of the substance 1°C

Specific Heat (Capacity)

- The greater the specific heat of a substance, the greater is the amount of heat required to raise the temperature of a unit of mass.
- Put another way, the greater the specific heat of a substance the greater its capacity to store more heat energy
- Water has a very high heat capacity, therefore can store large amounts of heat.

Specific Heats of Some Common Substances

<table>
<thead>
<tr>
<th>Substance</th>
<th>Specific Heat (20°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>J/kg°C</td>
</tr>
<tr>
<td>Air (6°C, 1 atm)</td>
<td>0.24</td>
</tr>
<tr>
<td>Alcohol (ethyl)</td>
<td>0.61</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.22</td>
</tr>
<tr>
<td>Copper</td>
<td>0.092</td>
</tr>
<tr>
<td>Glass</td>
<td>0.20</td>
</tr>
<tr>
<td>Human body (average)</td>
<td>0.83</td>
</tr>
<tr>
<td>Ice</td>
<td>0.51</td>
</tr>
<tr>
<td>Iron</td>
<td>0.105</td>
</tr>
<tr>
<td>Mercury</td>
<td>0.033</td>
</tr>
<tr>
<td>Silver</td>
<td>0.056</td>
</tr>
<tr>
<td>Soil (average)</td>
<td>0.25</td>
</tr>
<tr>
<td>Straw (at 1 atm)</td>
<td>0.30</td>
</tr>
<tr>
<td>Water (liquid)</td>
<td>1.000</td>
</tr>
<tr>
<td>Wood (average)</td>
<td>0.40</td>
</tr>
</tbody>
</table>

The three phases of water are highlighted.

Sand (700 J/kg-°C) & Water (4186 J/kg-°C)

Specific Heat Depends on Three Factors

- The specific heat or the amount of heat necessary to change the temperature of a given substance depends on three factors:
  1) The mass \( m \) of the substance
  2) The heat \( c \) of the substance
  3) The amount of temperature change \( \Delta T \)

Using Specific Heat

- \( H = mc\Delta T \)
  - \( H \) = amount of heat to change temperature
  - \( m \) = mass
  - \( c \) = specific heat capacity of the substance
  - \( \Delta T \) = change in temperature

- The equation above applies to a substance that does not undergo a phase change.
Using Specific Heat - Example

• How much heat in kcal does it take to heat 80 kg of bathwater from 12°C to 42°C?
• GIVEN: $m = 80$ kg, $\Delta T = 30^\circ C$, $c = 1.00$ kcal/kg°C (known value for water)
• $H = mc\Delta T = (80 \text{ kg})(1.00 \text{ kcal/kg°C})(30^\circ C)$
• Heat needed = $2.4 \times 10^3$ kcal

Electricity costs to heat water

• Heat needed = $2.4 \times 10^3$ kcal
• $\rightarrow$ Convert to kWh
• $(2.4 \times 10^3 \text{ kcal}) \frac{0.00116 \text{ kWh}}{\text{kcal}} = 2.8 \text{ kWh}$
• At 10 cents per kWh, it will cost 28 cents to heat the water in the bathtub.

Using Specific Heat - Confidence Exercise

• How much heat needs to be removed from a liter of water at 20°C so that it will cool to 5°C?
• GIVEN: 1 liter water = 1 kg = $m$
• $\Delta T = 15^\circ C$, $c = 1.00$ kcal/kg°C
• $H = mc\Delta T = (1 \text{ kg})(1.00 \text{ kcal/kg°C})(15^\circ C)$
• Heat removed = 15 kcal

Latent Heat

• Phases of matter $\rightarrow$ solid, liquid, or gas
• When a pot of water is heated to 100°C, some of the water will begin to change to steam.
• As heat continues to be added more water turns to steam but the temperature of the water remains at 100°C.
• Where does all this additional heat go?
• Basically this heat goes into breaking the bonds between the molecules and separating the molecules.

Latent Heat

• Hence, during a phase change (liquid to gas), the heat energy must be used to separate the molecules rather than add to their kinetic energy.
• The heat associated with a phase change (either solid to liquid or liquid to gas) is called latent (“hidden”) heat.

Latent Heats

• Latent Heat of Fusion ($L_f$) – the amount of heat required to change one kilogram of a substance from the solid to liquid phase at the melting point temperature
  – Occurs at the melting/freezing point
  – $L_f$ for water = 80 kcal/kg
• Latent Heat of Vaporization ($L_v$) – the amount of heat required to change one kilogram of a substance from the liquid to the gas phase at the boiling point temperature
  – Occurs at the boiling point
  – $L_v$ for water = 540 kcal/kg
• Latent heat of fusion – heat necessary to go from A to B
• Latent heat of vaporization – heat necessary to go from C to D

A=100% solid at 0°C
B=100% liquid at 0°C
C=100% liquid at 100°C
D=100% gas at 100°C

• Sublimation – when a substance changes directly from solid to gas (dry ice → CO₂ gas, mothballs, solid air fresheners)
• Deposition – when a substance changes directly from gas to solid (ice crystals that form on house windows in the winter)

Latent Heat of Fusion
Heat needed to Melt or Boil

• Latent Heat of Fusion ($L_f$) – the heat required can generally be computed by multiplying the mass of the substance by its latent heat of fusion.
• Heat to melt a substance = mass × latent heat of fusion
• $H = mL_f$

Latent Heat of Vaporization
Heat needed to Melt or Boil

• Latent Heat of Vaporization ($L_v$) – the heat required can generally be computed by multiplying the mass of the substance by its latent heat of vaporization
• Heat to melt a substance = mass × latent heat of vaporization
• $H = mL_v$
Latent heat – An Example

- Calculate the amount of heat necessary to change 0.20 kg of ice at 0°C into water at 10°C
- Two steps → both solid and liquid water
- \( H = H_{\text{melt ice}} + H_{\text{change T}} \)
- \( H_{\text{melt ice}} \) → phase change at 0°C (heat of fusion)
- \( H_{\text{change T}} \) → \( T \) change as a liquid, from 0 – 10°C
- \( H = mL + mc\Delta T \)
- \((0.20 \text{ kg})(80 \text{ kcal/kg}) + (0.20 \text{ kg})(1.00 \text{ kcal/kg°C})(10°C) = 18 \text{ kcal}\)

Pressure affects Phase Changes

- Increase pressures at lower altitudes increase boiling point
  - Pressure cooker – higher pressure leads to higher boiling point that allows a higher temperature that cooks the food faster!

High altitude

- Decrease pressure - Decreases boiling point
- Water boils at a lower temperature and must cook longer!

Evaporation – Cooling due to \( \Delta \) Phase

- In order for water to undergo a phase change from liquid to gas the molecules of water must acquire the necessary amount of heat (latent heat of vaporization) from somewhere.
  - In the case of sweat evaporating, some of this heat comes from a person’s body, therefore serving to cool the person’s body!
- More evaporation occurs in dry climates than in humid climates resulting in more cooling in dry climates.

Heat Transfer Occurs by Conduction, Convection, and Radiation

Conduction

- Conduction is the transfer of heat by molecular collisions.
- How well a substance conducts depends on the molecular bonding.
- Thermal Conductivity – the measure of a substance’s ability to conduct heat
- Liquids/gases – generally poor thermal conductors (thermal insulators) – because their molecules are farther apart, particularly gases
- Metals – generally good thermal conductors – because their molecules are close together
Convection

- **Convection** is the transfer of heat by the movement of a substance, or mass, from one position to another.
- Most homes are heated by convection. (movement of heated air)

Radiation

- **Radiation** is the process of transferring energy by means of electromagnetic waves.
  - Electromagnetic waves carry energy even through a vacuum.
- In general dark objects absorb radiation well and light colored objects do not absorb radiation well.

Insulation

- Good insulating material generally has an abundance of open air space to inhibit the movement of heat.
  - Goose down sleeping bags
- House insulation (spun fiberglass)
  - Pot holders (fabric with batting)
  - Double paned windows – void between glass panes

A vacuum bottle

- Incorporates principles of all three methods of heat transfer to help prevent the transfer of heat energy.

A Vacuum (thermos) Bottle

- Partial vacuum between the double walls minimizes the conduction and convection of heat energy.
- The silvered inner surface of the inner glass container minimizes heat transfer by radiation.
- Thus, a quality vacuum (thermos) bottle is designed to either keep cold foods cold or hot foods hot.

Phases of Matter

- **Solid, Liquid, and Gas** – the three common phases of matter
- Pressure and Temperature (P&T) determine in which phase a substance exists.
- Example at normal room P & T:
  - Copper is solid
  - Water is liquid
  - Oxygen is a gas
Solids (molecules vibrate)

- Have a definite shape and volume
- **Crystalline Solid** (minerals) – the molecules are arranged in a particular repeating pattern
  - Upon heating the molecules gain kinetic energy (vibrate more). The more heat the more/bigger the vibrations and the solids expand.
- **Amorphous Solid** (glass) – lack an ordered molecular structure
  - Gradually become softer as heat is added (no definite melting temperature)

Crystalline Lattice

- The 3-D orderly arrangement of atoms is called a lattice.
- Expansion of the lattice due to increase in temperature ($T$)

The outward appearance of a well-formed mineral reflects the molecular lattice. Halite (NaCl) is cubic in shape.

![Halite crystals](Photo Source: Copyright © Bobby H. Bammel. All rights reserved.)

Liquid

- The molecules may move and assume the shape of the container.
  - *Liquids only have little or no lattice arrangement.*
  - A liquid has a definite volume but no definite shape.
- Liquids expand when they are heated (molecules gain kinetic energy) until the boiling point is reached.

Gas/Vapor

- When the heat is sufficient to break the individual molecules apart from each other
  - *The gaseous phase has been reached when the molecules are completely free from each other.*
- Assumes the entire size and shape of the container
- Pressure, Volume, and Temperature are closely related in gases.

Plasma

- If a gas continues to be heated, eventually the molecules and atoms will be ripped apart due to the extreme kinetic energy.
- **Plasma** – an extremely hot gas of electrically charged particles
- Plasmas exist inside our sun and other very hot stars.
- The ionosphere of the Earth’s outer atmosphere is a plasma.
- Plasmas are considered another phase of matter.
Kinetic Theory of Gases

- A gas consists of molecules moving independently in all directions at high speeds.
- The higher the temperature the higher the average speed of the molecules.
- The gas molecules collide with each other and the walls of the container.
- The distance between molecules is, on average, large when compared to the size of the molecules.

Pressure (Gas)

- The result of the collisions of billions of gas molecules on the wall of a container (a balloon or ball for example)
  - more gas molecules
  - more collisions
  - more force on the container
  - therefore more pressure

Pressure

- Pressure is defined as force per unit area.
  - \( p = \frac{F}{A} \)
- SI Unit = N/m\(^2\) = pascal (Pa)
- Common Unit = atmosphere
  - 1 atm = normal atmospheric pressure at sea level and 0\(^\circ\)C
  - 1 atm = 1.01 X 10\(^5\) Pa = 14.7 lb/in\(^2\)

Pressure and # Molecules

- If the \( T \) and \( V \) are held constant, pressure is directly proportional to the number of gas molecules present: \( p \alpha N \)

Pressure and Kelvin Temperature

- If \( V \) and \( N \) are held constant, pressure is directly proportional to the Kelvin temperature: \( p \alpha T \)

Pressure and Volume

- If \( N \) and \( T \) are held constant, pressure and volume are found to be inversely proportional: \( p \alpha \frac{1}{V} \)
Factors affecting the Pressure of a Confined Gas (Ideal Gas Law)

- Pressure \( (p) \) is directly proportional to the number of molecules \( (N) \) and the Kelvin temperature \( (T) \). \( p \propto NT \)
- Pressure \( (p) \) is inversely proportional to the volume \( (V) \). \( p \propto \frac{1}{V} \)
- \( P \propto \frac{N}{V} \) \( \frac{T_2}{T_1} \)
- \( P_2 = \frac{T_2}{T_1} \cdot P_1 \)

N must be constant for this equation to be valid.

Ideal gas Law – an example

- A closed rigid container holds a particular amount of hydrogen gas. Initial pressure of 1.80 \( \times 10^6 \) Pa at 20°C. What will be the pressure at 40°C?
- GIVEN:
  - \( V_1 = V_2 \) (rigid container) & \( p_1, T_1, T_2 \)
  - Must convert \( T_1 \) and \( T_2 \) to Kelvin (add 273°)
- FIND: \( p_2 \)
- \( p_2 = \frac{T_2}{T_1} \cdot p_1 = (313K / 293K)(1.80 \times 10^6 \text{ Pa}) = 1.92 \times 10^6 \text{ Pa} \) (pressure increase, as expected)

Thermodynamics

- Deals with the dynamics of heat and the conversion of heat to work. (car engines, refrigerators, etc.)
- First Law of Thermodynamics – heat added to a closed system goes into the internal energy of the system and/or doing work
- \( H = \Delta E_i + W \) (1st Law of Thermodynamics)
  - \( H \) = heat added to a system
  - \( \Delta E_i \) = change in internal energy of system
  - \( W \) = work done by system

Schematic Diagram of a Heat Engine

- A Heat Engine takes heat from a high temperature reservoir, converts some to useful work, and rejects the remainder to the low-temperature reservoir.

Second Law of Thermodynamics

- It is impossible for heat to flow spontaneously from a colder body to a hotter body
- No heat engine operating in a cycle can convert all thermal energy into work. (100% thermal efficiency is impossible.)

Third Law of Thermodynamics

- It is impossible to attain a temperature of absolute zero.
- Absolute zero is the lower limit of temperature.
Schematic Diagram of a Heat Pump

- The work input transfers heat from a low-temperature reservoir to a high-temperature reservoir.
- In many ways it is the opposite of a heat engine.

Entropic Diagram of a Heat Pump

- The work input transfers heat from a low-temperature reservoir to a high-temperature reservoir.
- In many ways it is the opposite of a heat engine.

Entropy

- The change in entropy indicates whether or not a process can take place naturally.
  - *Entropy is associated with the second law.*
- Entropy is a measure of the disorder of a system.
  - Most natural processes lead to an increase in disorder. (Entropy increases.)
  - Energy must be expended to decrease entropy.
- Since heat naturally flows from high to low, the entire universe should eventually cool down to a final common temperature.