

ESCI 241 – Meteorology
Lesson 2 – Thermodynamics

ENERGY

- Energy is defined as *the capacity to do work*.
- There are two main categories of energy:
 - *Potential energy* – stored energy
 - Example: In a gravitational field, $PE = mgh$.
 - *Kinetic energy* – energy of motion
 - $KE = \frac{1}{2}mv^2$
- Other types of energy
 - *Thermal energy* – total of the kinetic energy of all the molecules in a substance
 - *Internal energy (U)* – the sum of thermal energy and any potential energy due to the forces between the molecules of a substance.
 - Note that for an ideal gas, since there are no intermolecular forces, there is no potential energy between molecules. Therefore, *for an ideal gas, internal energy and thermal energy are identical!*
- Energy is conserved
 - Energy can be converted from one form to another, but it cannot be created nor destroyed (this is the *1st Law of Thermodynamics*).

TEMPERATURE

- Temperature is related to the average translational kinetic energy of the molecules of a substance, $T \propto KE$.
- Hot objects have faster moving molecules. Cold objects have slower moving molecules
- Heat is energy that is in the process of being transferred from one object to another due to temperature differences.

TEMPERATURE SCALES

- Temperature scales are rather arbitrary. Meteorologists use three different scales.
- Fahrenheit (°F)
 - 0°F chosen as lowest temperature that a mixture of ice, water, and ammonia salt (ammonium chloride) can reach in equilibrium.
 - 32°F is the freezing point of pure water.
 - 96°F was originally chosen as the blood temperature of a healthy person (now 98.6°F on the modern Fahrenheit scale).
 - Fahrenheit's choice of his fixed points seems arbitrary, and his exact reasoning hasn't been recorded.

- Celsius (°C)
 - Zero point determined by freezing point of water
 - 100° point corresponds to boiling point of water.
 - Conversion from Celsius to Fahrenheit

$$F = \frac{9}{5}C + 32 \quad (1)$$

- A change of 1°C is equivalent to a change of 1K or 1.8°F.
- Kelvin (K)
 - Referred to as the *absolute* temperature scale
 - Zero point determined by the lowest theoretical temperature to which any matter can be cooled (*entropy, not energy, is zero at absolute zero*).
 - It is theoretically impossible to cool a substance to absolute zero in a finite number of steps, and therefore, a temperature of absolute zero is unattainable. This is known as the principle of unattainability of absolute zero.
 - The coldest temperature achieved so far (as of 2009) is 3×10^{-9} K.
 - Degree interval is same as in Celsius
 - Conversion from Kelvin to Celsius

$$C = K - 273.15 \quad (2)$$

- A change of 1K is equivalent to a change of 1°C or 1.8°F.

- **Note:** If you are interested in historical accounts of thermometers and the creation of the various temperature scales you can try the following two books: *A History of the Thermometer and its use in Meteorology* by W.E.K. Middleton, Johns Hopkins Press, 1966; or *Inventing Temperature: Measurement and Scientific Progress* by H. Chang, Oxford University Press, 2004.

FIRST LAW OF THERMODYNAMICS

- Energy is conserved.
- The internal energy (U) of an air parcel can be changed by either heating the parcel (Q) the parcel, or by doing work (W).

$$dU = dQ + dW \quad (3)$$

- Positive work implies work being done *on* the air parcel, whereas negative work implies work being done *by* the air parcel.
- An expanding air parcel does work on its environment ($dW < 0$). Therefore, *an expanding air parcel will lose internal energy, and cool.*
- Conversely, a shrinking air parcel has work done on it by the environment ($dW > 0$). Therefore, *a shrinking air parcel will gain internal energy, and warm.*

SENSIBLE HEAT AND HEAT CAPACITY

- Sensible heat results in a change of temperature.
- The amount of heat required to raise the temperature of an object by 1°C is called the *heat capacity*, C .
 - *Heat capacity depends on both the amount and type of the substance*
 - Units of heat capacity are J K^{-1}
- The heat capacity will depend on whether the pressure or volume changes during the heating.
 - If pressure is held constant, then the heat capacity is denoted as C_p .
 - If volume is held constant, then the heat capacity is denoted as C_v .
- Heat capacity per unit mass is called the *specific heat*

$$\begin{aligned} c_v &= C_v / m \\ c_p &= C_p / m \end{aligned} \quad (4)$$

- Units of specific heat are $\text{J kg}^{-1} \text{K}^{-1}$

- The specific heat at constant pressure is larger than the specific heat at constant volume.
 - This is because at constant volume, all the heat goes into raising the temperature, but at constant pressure the gas can also expand and do work, so some of the heat goes into doing work instead of raising the temperature.

PHASE CHANGES AND LATENT HEAT

- The amount of heat required to change the phase of a unit mass of a substance is called the *latent heat*.
 - The amount of latent heat depends on the substance and the process. The processes are:
 - *Melting* – solid to liquid, absorbs heat
 - *Freezing* – liquid to solid, releases heat
 - *Evaporation* – liquid to vapor, absorbs heat
 - *Condensation* – vapor to liquid, releases heat
 - *Sublimation* – solid to vapor, absorbs heat
 - *Deposition* – vapor to solid, releases heat
- Latent heating is an important heat source and sink for the atmosphere.

HEAT TRANSFER

- Heat can be moved or transported in one of three ways
 - *Conduction* – Transfer of heat through physical contact
 - *Convection* – Transfer of heat through movement of fluid
 - In Meteorology, the term convection is used solely for vertical transport by a fluid. Horizontal transport is referred to as *advection*.
 - *Radiation* – Transfer of heat through electromagnetic waves

EXERCISES

1. The specific heat of water at constant pressure is $1 \text{ cal g}^{-1} \text{ }^\circ\text{C}^{-1}$.
 - a. What is the heat capacity at constant pressure of 2 kg of water?
 - b. How much energy must be added to 2 kg of water to increase the temperature by 3°C ?
2. How much heat is released by the condensation of 3 kg of water vapor? (The latent heat of vaporization is 600 cal kg^{-1} .)
3. A 3 kg block of aluminum has a heat capacity (constant pressure) of 2691 J K^{-1} .
A 0.5 kg block of beryllium has a heat capacity (constant pressure) of 912 J K^{-1} .
Which one has a higher specific heat at constant pressure?
4. A 1.5 kg parcel of dry air is at a temperature of 15°C and a pressure of 1013 mb.
 - a. How many moles of air are in the parcel? (The molecular weight of air is 28.96 g/mol)
 - b. What is the volume of the parcel?
 - c. If 50 KJ of heat are added to the parcel while its volume is held constant, what is the new temperature of the parcel? (The specific heat of air at constant volume is $717 \text{ J kg}^{-1} \text{ K}^{-1}$).
 - d. If 50 KJ of heat are added to the parcel while its pressure is held constant, what is the new temperature of the parcel? (The specific heat of air at constant pressure is $1005 \text{ J kg}^{-1} \text{ K}^{-1}$).