PHS 105 LECTURE NOTES

(Part II – Heat and Thermodynamics)

By
O.I. Olusola (Ph.D.)

Course contents

Temperature, heat, thermometers, internal energy and Mechanical Equivalence of heat, Elementary treatment of the contents of the laws of thermodynamics.

Suggested references:

1. University Physics W. Sears
2. Fundamentals of Physics by J. Walker
3. Advance level Physics by Nelkon and Parker
4. College Physics by Frederick, J Beuche and Eugene Hecht

1.0 THERMODYNAMIC SYSTEMS & THERMAL EQUILIBRIUM

Thermodynamics involve the study of the relationship between heat and other forms of energy. It often involves production of heat from work or work from heat. The former occurs when we rub our palms together (i.e. mechanical work) to generate heat and the later when fuel is burnt (heat from automobile engine to generate motion of the wheels (mechanical work).

Chemical thermodynamics deals mainly with equilibrium states i.e. with systems which are in the thermodynamic equilibrium. To be in thermodynamic equilibrium, a system must be in mechanical, chemical and thermal equilibrium. This means that mechanical properties (e.g. pressured, chemical properties (e.g. composition) and thermal properties and thermal properties (e.g. temperature) must all be at "steady-state" i.e. they must not change with time.

If two systems A and B which are initially at different thermal states are brought into thermal contact, energy exchange will occur between the two systems until eventually both attain the same thermal state. At this point the then properties of A and B no longer vary with time and they are in thermal equilibrium.

The Zeroth law of thermodynamics states that two systems which are in their equilibirium with a third system are also in thermal equilibirium with each other.

1.1 FIRST LAW OF THERMODYNAMICS

The first law of thermodynamics is essentially the law of conservation of energy. It states that if a closed system absorbs a net amount of energy (heat) Q from its surroundings and does an amount of work (W), the quantity (Q-W) is used in raising the internal energy (μ) of the system.

Mathematically, first law of thermodynamic can be expressed as

$$Q - W = \Delta u \qquad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_(l)}$$

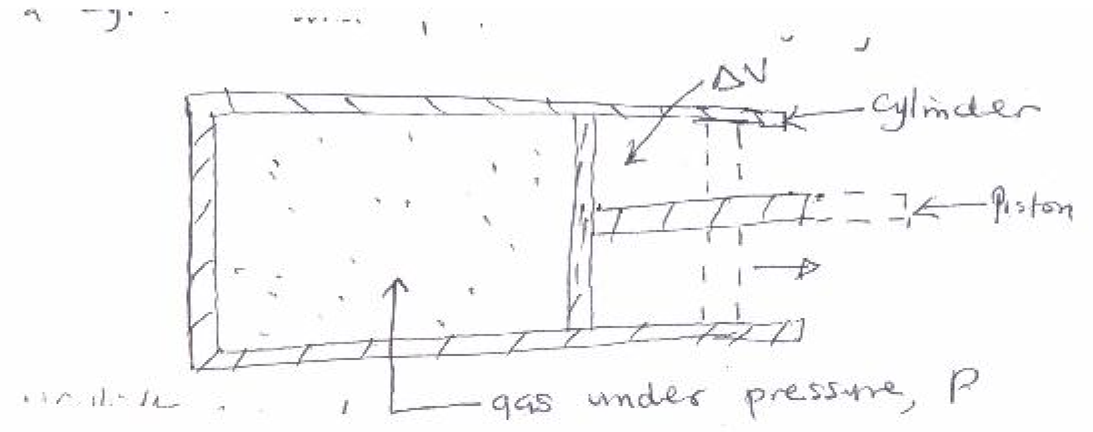
Where Δu is the change in internal energy of the system.

NOTES:

(i) Heat added to the system is positive

(ii) Heat released by the system is negative

Work is said to be done when any boundary of a system undergoes a displacement under the action of a force. Let us consider a system consisting of a gas under pressure P enclosed in a cylinder and piston unit [see Fig. 1]



The work (dW) done by the gas when the piston moves to the right under pressure P such that the volume of the gas increases by dV is

$$dW = PdV \qquad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_}(2)$$

If the piston moves through a finite distance, then the work done is given as

$$W = \int_{V_1}^{V_2} pdV \qquad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_}(3)$$

NOTES:

(1) Work done by the system is positive

(2) Work done on the system is negative

1.2 HEAT ENGINES

A heat engine is a device which produce work from a supply of heat. A common example of heat engine is the PETRO (or Gasoline) engine.

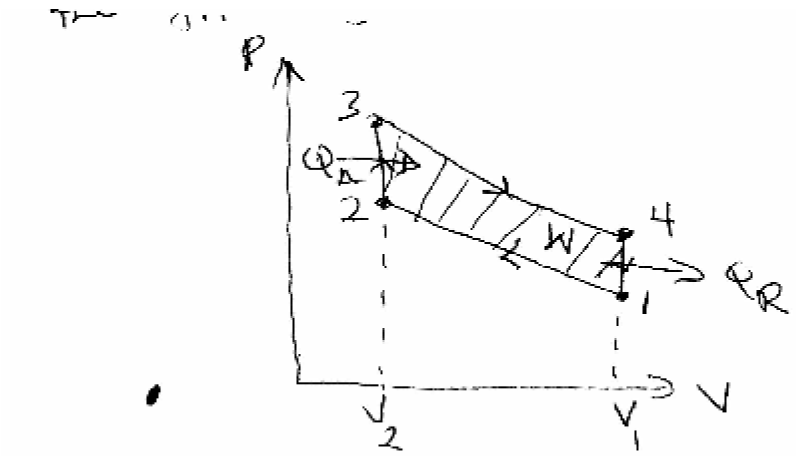
The working cycle for the petrol can be closely approximated by OTTO cycle which consists of four main processes namely;

1-2 Adrabatic compression of air-petrol mixture

2-3 Heating at constant volume to state 3

2-4 Adiabatic expansion to state 4

The above four processes can be represented by the following figure.



The net work produced by the engine is given by

$$Q_A - Q_R = W \quad \text{--(4)}$$

where Q_A is the heat added to the system while Q_R is the heat removed from the system.

We define thermal efficiency of a heat engine as the ratio of the work done by the engine to the heat added to the system i.e.

$$e_0 = \frac{W}{Q_A} = \frac{Q_A - Q_R}{Q_A}$$

or

$$e_0 = 1 - \frac{Q_R}{Q_A} \quad \text{--(5)}$$

1.3 SECOND LAW OF THERMODYNAMICS

The second lar of thermodynamics states that it is impossible to construct an engine which absorbs heat from a reservoir at a single temperature and converts all of the heat to work. The term "reservoir" is used to represent any part of a system which can absorb or release a large amount/quantity of heat without showing an appreciable change in temperature.

Based on the 2^{nd} law of thermodynamic it is impossible to build an engine with 100% efficiency, however, it is of interest to know the MAXIMUM possible efficiency that can be attained. The Carnot engine is an idealized engine that can produce about 100% efficiency. It consists of four REVERSIBLE processes (i.e. a process that can be made to reverse itself without external aid); these processes include:

1-2: Reversible adiabatic compression

2-3; Reversible isothermal expansion during which, heat Q_A is absorbed From heat reservoir, T_H

3-4 Reversible adiabatic expansion from T_H to T_c

4-1 Reversible isothermal compression during which heat, Q_R is rejected.

For a Carnot engine

$$\frac{T_C}{T_H} = \frac{Q_R}{Q_A} \qquad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_(6)}$$

The efficiency of a Carnot engine is given by

$$e_C = 1 - \frac{T_C}{T_H} \qquad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_(7)}$$

1.3 Solved Problems

(1) A Carnot engine is operated between two (2) heat reservoirs at temperature 400k and 300k. If the engine receives 200cal from 400k reservoir, (a) how many calories does it reject to the lower temperature reservoir? (b) What is the thermal efficiency of the engine?

Solution: For a Carnot engine

$$\frac{Tc}{TH} = \frac{QR}{QA}$$

(a) $\longrightarrow Q_R = Q_A \dfrac{T_c}{T_h}$

$Q_A =$ 2000 cal, Tc = 300, TH = 400

$\longrightarrow$

$$Q_R = 2000 \times \frac{300}{400}$$

$= 1{,}500$ cal.

(b) Thermal efficiency, $e = 1 - \dfrac{T_c}{T_H}$

$$= 1 - \frac{300}{400}$$

$= 0.25$ or 25%

(3) What is the maximum efficiency of an engine which operated between two reservoirs at temperatures of (a) 25^oC and 40^oC, and (b) 25^oC and 100^oC?

Solution: The maximum efficiency in the Carnot efficiency.

(a) ec = $1 - T_c/T_H$, where Tc = 25^oc = 25+273

= 298k, $T_H = 40^oC$ = (40+273)K = 313K

$:: e_c = 1 - \frac{298}{313} = 4.79\%$

(b) $e_c = 1 - \frac{Tc}{TH}$, where Tc = 298k, TH = 373

$::: e_c = 1 - \frac{298}{373} = 20.11\%$

1.5 HEAT CAPACITY

The heat capacity of a body, such as a lump of metal, is the quantity of heat required to raise the temperature of such body by 1K. It is measure in J/K.

Assume that a small quantity of heat, dQ, is transferred between a system of mass m and its surrounding, If the system undergoes a small temperature change, dT, the specific heat capacity, c, of the system is defined as

$$c = \frac{1}{m}.\frac{dQ}{dt} \qquad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_(8)}$$

From Eq. 8, it is easy to show that the heat dQ needed to raise the temperature of mass, m, of material by an amount dT is

$$dQ = mcdT \qquad \text{\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_(9)}$$

c is measured in J/Kg/K e-g c for water is $4200 J/kg^{-1}k^{-1}$, or $4.2\ Jg^{-1}K^{-1}$

2.1 The Concept of Temperature

The concept of temperature plays an important role in both biological and physical sciences because the temperature of an object is directly related to average k.e of the atoms and molecules composing the object. The temperature of a body is therefore define as the property of the body that determines whether or not the body/system is in thermal equilibrium with another body.

2.2 Temperature Scales

Some of the commonly encountered temperature scale include: Fahrenheit scale,; O^oC and 100^oC on the Celsius scale; and 273.15k and 373.15 on the Kelvin scale.

The Celcius temperature T_c, is related to Fahrenheit, Tc, according to the equation:

$$T_c = {}^5/_9 \ (T_F - 32)$$

The Kelvin temperature, T_k is an absorbent temperature scale, it is related to the celcius temperature, T_F, by the equation.

$$Tk = Tc + 273.15 \quad \underline{\hspace{6cm}}(2)$$

Furthermore, the Fahrenheit temperature is related to the Celcius temperature according to the equation.

$$T_F = {}^9/_5 \ (T_c) + 32 \quad \underline{\hspace{6cm}}(3)$$

NOTE: In order to convert from Fahrenheit to Kelvin temperature scale, one needs to convert the ^{o}F to ^{o}C and finally from ^{o}C to K.

2.3 WORKED EXAMPPLES

(1) Calculate the equivalent of 98.6^oF in ^oC.

Solution: $T_F = 98 \ 6^oF$, Tc =?

We know that $Tc = {}^5/_9 \ (T_F - 32)$

$$= {}^5/_9 * (98.6-32)$$

$$= {}^5/_9 * 66.6^oF$$

$$= 37.0^oC.$$

(2) The reading on the pressure scale at steam and ice points are 800mm and 200mm respectively. Determine the equivalent

Temperature (in ^oC) when it reads 450mm.

Solution. $P\theta = 300$, $P_{100} = 800$, $P = 450mm$

The temperature θ in ^oC is given by

$$\theta = \frac{P\theta - P_o}{P_{100} - P_o} \times 100\ ^oC$$

$$= \frac{450 - 300}{800 - 300} \times 100$$

$$= 30^oC$$