MACHAKOS UNIVERSITY

University Examinations 2023/2024

SCHOOL OF PURE AND APPLIED SCIENCES

DEPARTMENT OF PHYSICAL SCIENCES

THIRD YEAR FIRST SEMESTER EXAMINATION FOR

BACHELOR OF SCIENCE IN APPLIED PHYSICS AND TECHNOLOGY

SPT 303: THERMAL PHYSICS II

DATE: **TIME:**

INSTRUCTIONS:

- The paper consists of **two** sections.
- Section **A** is **compulsory** (30 marks).
- Answer any **two** questions from section **B** (each 20 marks).

Useful information

Universal gas constant, $R = 8.314$ J/kg/mol

Isothermal compressibility, $K_T = -\frac{1}{V}\left(\frac{\partial V}{\partial p}\right)_T$

Adiabatic compressibility, $\beta = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)_P$

1 atmosphere $= 1.013 \times 10^5$ Pa

Boltzmann's constant, $k_B = 1.38 \times 10^{-23}$ J/K

Specific heat capacity of water, $c = 4.186$ kJ/kg/K

Specific heat capacity of aluminum, $c_{al} = 0.902$ kJ/kg/K

1 calorie = 4.184 joules

QUESTION ONE

a) Explain briefly what you understand by the following terms,

(i) Entropy **(2 marks)**

(ii) Heat reservoir **(2 marks)**

b) A steam engine operating between a boiler temperature of 220^0C and a condenser temperature of 35^0C delivers 5.965 kW. If its efficiency is 30% of that for a Carnot engine operating between these temperature limits, how many kilo-joules are exhausted to the condenser each second? **(4 marks)**

c) Joule-Kelvin coefficient μ_j is a measure of the temperature change during a throttling process. A similar measure of temperature change produced by an isentropic change of pressure is provided by the coefficient μ_s where $\mu_s = \left(\frac{\partial T}{\partial p}\right)_S$. Prove that

$$\mu_s - \mu_j = \frac{V}{C_p}.$$ **(4 marks)**

d) The entropy of water at atmospheric pressure and 100^0C is $0.31\ \text{cal/g.}^0\text{C}$ and the entropy of steam at the same temperature and pressure is $1.76\ \text{cal/g.}^0\text{C}$.

i. What is the heat of vaporization at this temperature? **(2 marks)**

ii. The enthalpy ($H = U + PV$) of the steam under these conditions is 640 cal/g. Calculate the enthalpy of water under these conditions. **(3 marks)**

iii. Calculate the Gibbs free energy ($G = H - TS$) of water and steam under these conditions. **(3 marks)**

e) Show that the third law of thermodynamics implies that any heat capacity of a substance must vanish at absolute zero. **(3 marks)**

f) An aluminum metal of mass 2.5 kg at 100 ^{0}C is placed in a large insulated tank of water of mass 8.0 kg at 30 ^{0}C. Find

(i) the final equilibrium temperature of the aluminum and water, and **(2 marks)**

(ii) the entropy change of the universe. **(3 marks)**

QUESTION TWO

a) Use the following TdS equations to show that $C_p - C_v = (TV\beta^2)/K_T$. **(4 marks)**

$$TdS = C_v dT + T\left(\frac{\partial P}{\partial T}\right)_v dV$$

$$TdS = C_p dT - T\left(\frac{\partial V}{\partial T}\right)_p dP$$

b) Liquid Helium-4 has a normal boiling point of 4.2 K. However, at a pressure of 1 atmosphere, it boils at 1.2 K. Estimate the Latent heat of vaporization of Helium in this temperature range. Assume vapor is ideal gas. **(4 marks)**

c) Starting from the first law of thermodynamics and with the help of Maxwell relation, $\left(\frac{\partial S}{\partial V}\right)_T = \left(\frac{\partial P}{\partial T}\right)_V$ derive the first energy equation,

$$\left(\frac{\partial U}{\partial V}\right)_T = T\left(\frac{\partial P}{\partial T}\right)_V - P .$$ **(3 marks)**

d) (i) What does the following expression mean; **(2 marks)**

$$N(p)dp = N\left(\frac{2}{\pi}\right)^{1/2} . \left(\frac{1}{mk_BT}\right)^{3/2} . \exp\left\{-\frac{p^2}{2mk_BT}\right\} . p^2 . dp$$

(ii) Write down the equivalent expression for a system's velocity. **(2 marks)**

e) Show that the free enthalpy and its derivative with respect to temperature can be related to the enthalpy of the system via the Gibbs-Helmholtz equation. **(5 marks)**

$$H = G - T\left(\frac{\partial G}{\partial T}\right)_P = -T^2\left(\frac{\partial (G/T)}{\partial T}\right)_P .$$

QUESTION THREE

a) From the fundamental relation of the internal energy $U = U(S, V, N)$, show that $\left(\frac{\partial P}{\partial S}\right)_{V,N} = -\left(\frac{\partial T}{\partial V}\right)_{S,N}$, where S, V and N are standard thermodynamic symbols, and P and T are intensive parameters for pressure and temperature, respectively. **(4 marks)**

b) The fundamental relation for a particular thermodynamic system is given by

$$U = \frac{N^{5/3}}{V^{2/3}} \exp\left(\frac{2S}{3NR}\right)$$

Transform the fundamental relation into the Helmholtz free energy representation. **(5 marks)**

c) A reversible heat engine operates within three constant-temperature reservoirs at 100 K, 200 K, and 300 K. The engine receives 2500 kJ of energy as heat from the reservoir at 300 K and does 1000 kJ of work.

(i) Determine the heat rejected to the other reservoirs **(4 marks)**

(ii) Find the change in entropy in each reservoir and the change in entropy of the universe. **(3 marks)**

d) Starting with the fundamental equation for enthalpy and using the appropriate Maxwell relation, derive the following:

$$\left(\frac{\partial H}{\partial P}\right)_T = V - T\left(\frac{\partial V}{\partial T}\right)_P$$

Prove that for one mole of an ideal gas that $\left(\frac{\partial H}{\partial P}\right)_T = 0$. What is the equivalent for in a Van der Waal's gas? **(4 marks)**

QUESTION FOUR

a) (i) Describe the Clausius inequality and state its significance. **(2 marks)**

b) With the aid of thermodynamic diagrams, show that if the Kelvin-Planck statement of the second law is violated then the Clausius statement is also violated. **(4 marks)**

c) One kilogram of water is heated by an electrical resistor from 20°C to 99°C at constant pressure (atmospheric). Estimate:

d) The change in internal energy of the water. **(2 marks)**

e) The entropy change of the water. **(2 marks)**

f) Two Carnot engines A and B operate in series between a temperature reservoir at $1500\ \mathrm{K}$ and a low temperature reservoir at $300\ \mathrm{K}$. Engine A absorbs energy from the high temperature reservoir and rejects energy to engine B. Engine B rejects heat energy to the low temperature reservoir at $300\ \mathrm{K}$. If both engines have the same efficiency, determine;

g) the temperature at which engine A rejects energy as heat. **(4 marks)**

h) the work done by engine A and engine B if engine A absorbs 1000 kJ of energy as heat from the high temperature reservoir. **(6 marks)**

QUESTION FIVE

a) Define the following terms in thermodynamics

(i) Enthalpy **(2 marks)**

(ii) Reversibility **(2 marks)**

b) A frictionless piston is used to provide a constant pressure of 400 kPa in a cylinder containing steam originally at 200°C with a volume of 2 m^3. Calculate the final temperature if 3500 kJ of heat is added. **(4 marks)**

c) The specific heat of superheated steam at approximately 150 kPa can be determined by the equation

$$c_p = 2.07 + \frac{T - 400}{1480} \quad \mathrm{kJ/kg\ ^0C}$$

Calculate

(i) The enthalpy change between $300\,^oC$ and $700\,^oC$ for 3 kg of steam. **(4 marks)**

(ii) The average value of c_p between $300\,^oC$ and $700\,^oC$ based on the equation. **(4 marks)**

d) For the cycle in Figure 1 calculate the work output and the net heat transfer if 0.1 moles of air is contained in a piston-cylinder arrangement. **(4 marks)**

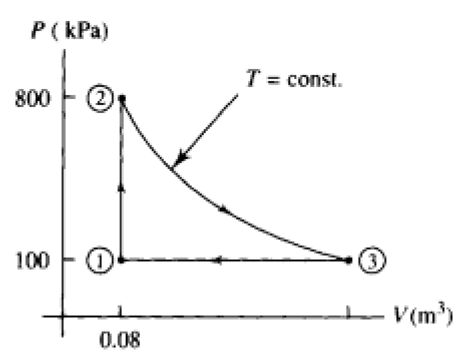

Figure 1