ME 661: Final: 9th November 2015 : 3 Hours [100pts]

- Closed book and closed notes.
- Steam tables and calculators allowed. Any number of A4 size handwritten cheat sheets allowed.
- No sharing of any materials.
- Write your name and roll number on both sides of all pages of cheat sheet.
- *If you feel there is some required data missing, make a reasonable assumption and underline the same.*

1. 1 kilogram of water is heated from 20^oC to 99^oC at 1 atmosphere pressure. Estimate the ratio of quantum states available at the final state to that of the initial state. Also find the amount of work saved if the heating is done using a Carnot heat pump instead of an electrical resistor. [5,5]

2. For a monoatomic ideal gas find the expression for Helmholtz free energy $F(= U - TS)$ as a function of number of moles n,V and T, from its equation of state and the molal specific heat at constant volume $C_v = 3R/2$.

   Now imagine a cylinder whose volume is separated into two parts a and b each containing 1 mole of this ideal gas by an impermeable adiabatic piston. The initial ratio of volumes of $a : b$ is 10. The cylinder is now placed in an immersion bath at 0^oC and heat transfer is allowed through the cylinder walls. The final ratio of the volumes is $a : b$ is $6 : 5$. Compute the work done on the system. [5,5]

3. An adiabatic sealed cylinder is fitted with a frictionless, conducting piston. Initially the piston divides the cylinder into two equal halves, one side contains 1 litre of air at 300K, 1 atm and the other side is at 500K and 3 atm. The piston is released and then equilibrium is reached. Compute the final pressure and temperature of the system, the new position of the piston and the total increase in entropy. [3,3,4]

4. Determine the ratio (PV/RT) at the critical point for a gas which obeys the following equation of state. [5]

$$P(V - b) = RTe^{\frac{-a}{RTV}}$$

5. Liquid octane (C_8H_{18}) enters a steady-flow combustion chamber at 25C and 1 atm at a rate of 0.25 kg/min. It is burned with 50 percent excess air that also enters at 25C and 1 atm. After combustion, the products are allowed to cool to 25C. Assuming complete combustion and that all the H_2O in the products is in liquid form, determine

   (a) The heat transfer rate from the combustion chamber. [5]

   (b) The entropy generation rate. [5]

   (c) The exergy destruction rate. [5]

   Assume that $T_0 = 298$ K and the products leave the combustion chamber at 1 atm pressure.

6. Construct a diagram showing the possible microstates of a system having the following energy levels, if the number of indistinguishable particles are 4 and the total energy is $U = 10\epsilon$. The energy levels are, $[0, \epsilon, 2\epsilon, 4\epsilon, 8\epsilon, 16\epsilon \ldots]$. The degeneracy at each level is 3. Assume that the system obeys B–E statistics. Calculate the thermodynamic probability of each macrostate and the total number of possible microstates. Also find the average occupation number in each level. Solve the same for F–D statistics. [10]

7. For a certain indistinguishable set of N particles the three lowest energy levels are $[0, \epsilon, 10\epsilon]$. Below what temperature will only levels 0 and ϵ be populated? Also derive an expression for C_v as a function of T for such a system and sketch C_v vs T. [5,5]

8. In a two–dimensional gas the molecules can move freely on a plane but are confined within an area A. (a) Show that the partition function for the two–dimensional monoatomic gas of N particles is given by

$$Z = \frac{2A\pi mkT}{h^2}$$

(b) Also find the equation of state for this gas from the Helmholtz function. [5,5]

9. The resistance of 2m of 0.01cm diameter copper wire is measured to be 3Ω. The density of copper wire is 8900 kg/m^3 and its atomic weight is 64.

   (a) Determine the mean free time τ between collisions of the electrons with the copper ion cores. [5]

   (b) Determine the mean free path of the electrons assuming that $\bar{v}$ for an electron is given by $\sqrt{\frac{8kT}{\pi m}}$. How many atomic distances is this, assuming that copper structure is cubic? [5]

   (c) Determine the ratio of the diameter of the copper ion cores to the atomic distance. [5]

   (d) Determine the average length of time it takes an electron to move the length of wire when the current through the wire is 0.333 A. [5] .

Substance	h_f^0 kJ/kmol	$\bar{h}_{298K}$ kJ/kMol	$\bar{s}^0$ kJ/kMol.K
CH_4	-74,850	–	186.16
$C_8H_{18}(l)$	-249,950	–	360.79
H_2	0	–	130.68
O_2	0	8682	205.04
N_2	0	8669	191.61
$H_20(g)$	-241,820	9904	188.83
CO_2	-393,520	9364	213.80
CO	-110,530	8669	197.65

ME 661: Midsem 3: 12th October 2015 : 2 Hours [100pts]

- Closed book and closed notes.
- Steam tables and calculators allowed. One A4 size handwritten cheat sheet allowed.
- No sharing of any materials.
- Write your name and roll number on both sides of the cheat sheet.
- *If you feel there is some required data missing, make a reasonable assumption and underline the same.*

1. Assume that the earth's atmosphere is made up of an ideal gas with molecular weight M. It also has an uniform acceleration of gravity g for the domain of interest.
   (a) Derive an differential expression for variation of pressure, p with altitude z which is given by
   $$\frac{1}{p}dp = -\frac{Mg}{RT}dz$$
   where R is the gas constant and T is the temperature. [5]
   (b) If the pressure decreases with height due to adiabatic expansion. Prove that
   $$\frac{1}{p}dp = \frac{\gamma}{\gamma-1}\frac{dT}{T}, \quad \gamma = \frac{C_p}{C_V} \qquad [5]$$
   (c) Evaluate $\frac{dT}{dz}$ for a pure N_2 atmosphere. $\gamma = 1.4$ [5]
   (d) If the atmosphere is assumed to be isothermal. Find $p(z)$ in terms of T and p_0 the pressure at sea level. [5]
   (e) Derive expression for $p(z)$ for an adiabatic atmosphere assuming that at sea level $p = p_0$ and $T = T_0$. [5]

2. An insulated tank that contains 1 kg of O_2 at 15 C and 300 kPa is connected to a 2 m^3 uninsulated tank that contains N_2 at 50 C and 500 kPa. The valve connecting the two tanks is opened, and the two gases form a homogeneous mixture at 25 C. Determine, (a) the final pressure of the tank, (b) the heat transfer and (c) the entropy generated during the process. Assume T_0= 25 C. The constant volume specific heats of O_2 and N_2 are 0.658 kJ/kg C and 0.743 kJ/kg C, respectively. [5,5,5]

3. A gaseous fuel with 80 percent CH_4, 15 percent N_2, and 5 percent O_2 (on a mole basis) is burned to completion with 120 percent theoretical air that enters the combustion chamber at 30 C, 100 kPa, and 60 percent relative humidity. Determine (a) the airfuel ratio and (b) the volume flow rate of air required to burn fuel at a rate of 2 kg/min. [5,5]

4. A mixture of 40 percent by volume methane CH_4, and 60 percent by volume propane C_3H_8, is burned completely with theoretical air and leaves the combustion chamber at 100 C. The products have a pressure of 100 kPa and are cooled at constant pressure to 39 C. Sketch the T-s diagram for the water vapor that does not condense, if any. How much of the water formed during the combustion process will be condensed, in kmol H2O/kmol fuel? [5,5]

5. Bowling pins with an effective diameter of 10cm are placed randomly on a bowling green (flat ground) with an average density of 10 pins per square meter. A large number of 10cm diameter bowling balls are bowled at the pins. (a) What is the ratio of the mean free path of the bowling ball to the average distance between the pins? (b) what fraction of the bowling balls will travel at least 3 meters without striking a pin? [5,5]

6. You are an ISRO engineer in India's manned space mission project working on designing the hull of the spaceship. The manned re–enty vehicle has a volume of $100m^3$ and the temperature is maintained at 285 K. In the event of a hull breach in orbit due to space debris, it will take at most 8 hours for re-entry and return to safety on the surface of the planet. The vehicle is pressurized at 1 atm and the lowest safe pressure that can be reached without putting the crew in jeopardy is 0.7 atm. What is the largest possible circular breach that can be tolerated assuming pure efflux out of this aperture from the cabin? [30]

ME 661: Midsem 1: 17th August 2015 : 2 Hours [100pts]

- Write your name and roll number on the first page of the answerbook.
- Closed book and closed notes.
- Steam tables and calculators allowed. One A4 size handwritten cheat sheet allowed.
- No sharing of any materials.
- Write your name and roll number on both sides of the cheat sheet.
- *If you feel there is some required data missing, make a reasonable assumption and underline the same.*

1. An ideal gas is isothermally compressed from a volume V_1 to a volume V_2 at a constant temperature T. It is subsequently expanded adiabatically to a volume V_3 which is twice V_2.

   (a) Show the process on a PV diagram and derive from first principles the net work and heat transfer for the ideal gas. [4]

   (b) Derive an expression for the final temperature T_f of the gas in terms of the initial temperature T. [4]

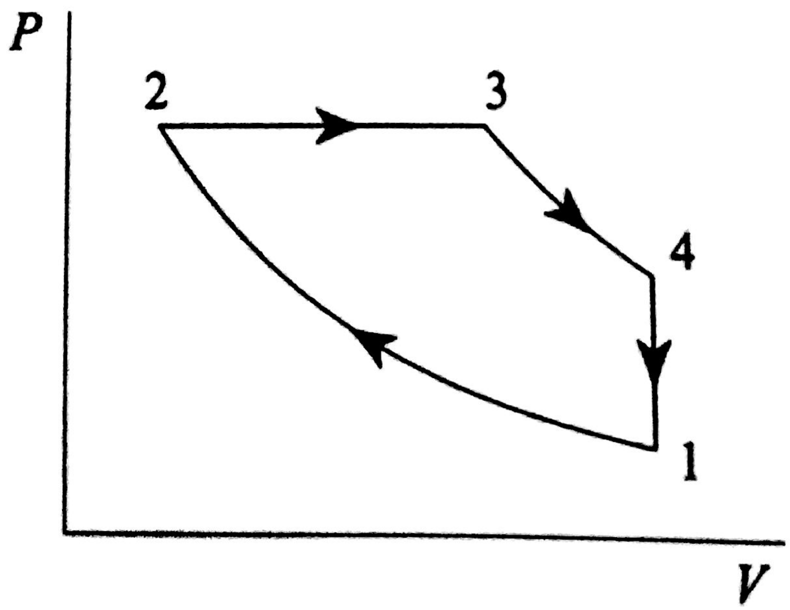
   (c) Estimate T_f for air, if the initial temperature of air is $300K$. [2]

2. A room is losing heat to surroundings at an absolute temperature of T_s at a rate of $\alpha(T - T_s)$, where T is the absolute temperature of the room and α is some constant.

   (a) Consider an ideal heat pump operating between the surroundings and the room which is now compensating for the heat loss to the surrounding. Derive an expression for the temperature $T_{e,HP}$, of the room once equilibrium is achieved. [5]

   (b) If instead of the heat pump, an electrical resistance heater is used, what will be the temperature $T_{e,res}$ of the room once equilibrium is reached. Show that $T_{e,res}$ is less than $T_{e,HP}$. [5]

3. Calculate the maximum possible efficiency of a Diesel cycle in terms of the pressure ratio r and cutoff ratio α. The diesel cycle is consists of an adiabatic process 1–2, constant pressure 2–3, an adiabatic 3–4 and a constant volume 4–1 as shown in the figure. Pressure ratio is defined as $r = \frac{V_1}{V_2}$ and cutoff ratio $\alpha = \frac{V_3}{V_2}$. [10]



4. Steam at $6000kPa$ and 500^oC enters a steady–flow turbine. The steam expands in the turbine while doing work until the pressure is $1000kPa$. When the pressure is $1000kPa$, 10 percent of the steam is removed from the turbine for other uses. The remaining 90 percent of the steam continues to expand through the turbine while doing work and leaves the turbine at $10kPa$. The entire expansion process by the steam through the turbine is reversible and adiabatic.

   (a) Sketch the process on a T–s diagram with respect to the saturation lines. Be sure to label the data states and the lines of constant pressure. [3]

   (b) If the turbine has an isentropic efficiency of 85 percent, what is the work done by the steam as it flows through the turbine per unit mass of steam flowing into the turbine, in kJ/kg? [7]

5. September 11th is infamous in history books due to the events that occurred in the year 2001. Some theories floating around claim that a passenger plane crashing into a building the size of the erstwhile World Trade Center in New York is not sufficient to bring the whole structure down. Let us begin to deconstruct this event through the unbiased eyes of thermodynamics. The aircraft involved in the incident was a Boeing 767-200ER (for one of the towers) whose maximum take–off weight is 179,170 kgs. At the time of the impact, assume that the plane was carrying about 90,000 litres of aviation fuel whose calorific value is 44 MJ/kg and density is 700 kg/m^3. The speed at impact was 0.86 mach, the maximum speed of the aircraft. Determine

   (a) The amount of energy dissipated, with the assumption that all of the jet fuel is burnt soon after impact. [5]

   (b) Given that the specific heat of structural steel is 0.5 kJ/kgK and the melting point of steel is 1425 C, what mass of steel, initially at 30C, can reach the melting point. [5]

   (c) If the same aircraft with negligible amount of fuel had impacted the building and the total amount of structural steel in the building is assumed to be 100,000 metric tons, calculate the maximum possible temperature rise for 20% of the structural steel. [5]

6. A large insulated jar of volume V_0 contains an ideal gas. The mouth of the jar is fitted (no gaps) with glass tube of cross–sectional area A in which a metal ball of mass M fits snugly. Due to the weight of the ball the equilibrium pressure in the jar is exceeds the atmospheric pressure p_0 by a small amount. Displacement of the ball from the equilibrium position will result in execution of simple harmonic motion (neglecting friction). Determine an expression relating the oscillation frequency f of the metal ball and the other parameters of the problem. [15]

   (Hint: $f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$ for SHM)

7. One kilogram of water at atmospheric pressure and 0^oC exchanges heat rapidly with a thermal reservoir at 100^oC.

   (a) Determine the entropy change of the water when equilibrium is attained. Also determine the entropy changes in the reservoir and the entire system. [6]

   (b) If the same amount of water had been heated in two steps where in the first step it is brought in touch with a thermal reservoir at 50^oC and then with subsequently with a reservoir at 100^oC, what are the entropy changes? [6]

   (c) In order to heat the water from 0^oC to 100^oC without any change in the entropy, what could be a theoretically possible process? [3]

8. One kilogram of helium which is initially at $100kPa$ and $300K$ undergoes a three–process reversible cycle. Process 1–2 is constant volume, process 2–3 is a constant pressure process and process 3–1 is isothermal. The ratio of volumes at state 1 and state 3 is 5 (i.e $\frac{v_1}{v_3} = 5$).

   (a) Determine the pressure, temperature and volume at states 1,2 and 3. [9]

   (b) Work done during the cycle. [3]

   (c) Heat transfer during process 3–1. [3]

Nothing in life is certain except death, taxes and the second law of thermodynamics.

– Seth Lloyd

ME 661: Midsem 2: 8th September 2015 : 2 Hours [100pts]

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- Steam tables and calculators allowed. One A4 size handwritten cheat sheet allowed.
- No sharing of any materials.
- Write your name and roll number on both sides of the cheat sheet.
- *If you feel there is some required data missing, make a reasonable assumption and underline the same.*

1. Starting with the first law of thermodynamics and the definitions of c_p and c_v, show that

$$c_p - c_v = \left(p + \left(\frac{\partial U}{\partial V}\right)_T\right)\left(\frac{\partial V}{\partial T}\right)_p$$

where c_p and c_v, are the specific heat capacities per mole at constant pressure and volume, respectively, and U and V are internal energy and volume of one mole. Use the above results and the below expression

$$p + \left(\frac{\partial U}{\partial V}\right)_T = T\left(\frac{\partial p}{\partial T}\right)_V$$

to find $c_p - c_v$, for a Van der Waals gas. Use that result to show that as $V \to \infty$ at constant p, you obtain the ideal gas result for $c_p - c_v$. [20]

simplify

2. The internal energy of a van der Waals gas is given by the expression, $u = cT - \frac{a}{V}$, where V is the molar volume, a is one of the van der Waals constants and c is some other constant. Derive expressions for the molar heat capacities $\bar{c}_p$ and $\bar{c}_v$. [15]

3. Consider a reversible Carnot engine working between two thermal reservoirs at temperatures of T_H and T_L, with $T_H > T_L$. It is assumed that the reservoir at T_L has nearly infinite mass and hence T_L practically remains a constant. While the reservoir at T_H is a gas of N moles held at constant volume. The C_v of this gas is a constant. The heat engine is now operated until the temperatures of both the reservoirs are equal. Determine the following,

   (a) Heat extracted from higher temperature reservoir. [3]

   (b) Change in entropy of higher temperature reservoir. [6]

   (c) Total work done by the heat engine. [6]

4. Chickens with an average mass of 2.2 kg and average specific heat of 3.54 kJ/kgC are to be cooled by chilled water that enters a continuous-flow-type immersion chiller at 0.5C and leaves at 2.5C. Chickens are dropped into the chiller at a uniform temperature of 15C at a rate of 500 chickens per hour and are cooled to an average temperature of 3C before they are taken out. The chiller gains heat from the surroundings at a rate of 200 kJ/h. Determine (a) the rate of heat removal from the chicken, in kW, and (b) the rate of exergy destruction during this chilling process. Take $T_0 = 25C$ [15]

5. Derive a relation for the Joule-Thomson coefficient and the inversion temperature for gases which have following equation of states.

   (a) Redlich–Kwong EOS $\to P(v-b) = RT$ [5]

   simplify

   (b) van der Waals EOS $\to (P + \frac{a}{v^2})(v-b) = RT$ [5]

   (c) $(P + \frac{a}{v^2})v = RT$ [5]

6. In a dairy plant, milk at 4^oC is pasteurized continuously at 72^oC at a rate of $12L/s$ for 24 hours per day and 365 days a year. The milk is heated to the pasteurizing temperature by hot water heated in a natural gas-fired boiler having an efficiency of 82 percent. The pasteurized milk is then cooled by cold water at 18^oC before it is finally refrigerated back to 4^oC. To save energy and money, the plant installs a regenerator that has an effectiveness of 82 percent. If the cost of natural gas is Rs.$0.005/kJ$, determine how much energy and money the regenerator will save this company per year and the annual reduction in exergy destruction. [20]