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Mechanical Engineering : Indian Forest Service Main Examination: (Paper-II)

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Preface

Our country has a vast forest cover of near about 25% of geographical area and if man doesn't learn to treat trees with respect, man will become extinct; Death of forest is end of our life. Scientific management and judicious exploitation of forest becomes first task for sustainable development.

Engineer is one such profession which has an inbuilt word "Engineer – skillful arrangement" and hence IFS is one of the most talked about jobs among engineers to contribute their knowledge and skills for the arrangement and management for sustainable development

In order to reach to the estimable position of Divisional Forest Officer (DFO), one needs to take an arduous journey of Indian Forest Service Examination. Focused approach and strong determination are the pre-requisites for this journey. Besides this, a good book also comes in the list of essential commodity of this odyssey.

I feel extremely glad to launch the revised edition of such a book which will not only make Indian Forest Service Examination plain sailing, but also with 100% clarity in concepts.

MADE EASY team has prepared this book with utmost care and thorough study of all previous years' papers of Indian Forest Service Examination. The book aims to provide complete solution to all previous years' questions with accuracy.

On doing a detailed analysis of previous years' Indian Forest Service Examination question papers, it came to light that a good percentage of questions have been asked in Engineering Services, Indian Forest Services and State Services exams. Hence, this book is a one stop shop for all Indian Forest Service Examination, CSE, ESE and other competitive exam aspirants.

I would like to acknowledge efforts of entire MADE EASY team who worked day and night to solve previous years' papers in a limited time frame and I hope this book will prove to be an essential tool to succeed in competitive exams and my desire to serve student fraternity by providing best study material and quality guidance will get accomplished.



B. Singh (Ex. IES)

With Best Wishes

B. Singh

CMD, MADE EASY Group

Previous Years Solved Papers

Indian Forest Service Main Examination

Mechanical Engineering

Paper-II

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SYLLABUS

Paper - II

1. THERMODYNAMICS: Basic concept, Open and closed systems, Applications of Thermodynamic Laws, Gas equations, Clapeyron equation, Availability, Irreversibility and T ds relations.
2. I.C. Engines, Fuels and Combustion: Spark Ignition and compression ignition engines, four stroke engine and two stroke engines, mechanical, thermal and volumetric efficiency, Heat balance. Combustion process in S.I. and C.I. engines, pre-ignition detonation in S.I. engine Diesel knock in C.I. engine. Choice of engine fuels, Octane and Cetane ratings. Alternate fuels Carburetion and Fuel injection, Engine emissions and control, Solid, liquid and gaseous fuels, stoichiometric air requirements and excess air factor, fuel gas analysis, higher and lower calorific values and their measurements.
3. HEAT TRANSFER, REFRIGERATION AND AIR CONDITIONING: One and two dimensional heat conduction. Heat transfer from extended surfaces, heat transfer by forced and free convection. Heat exchangers, Fundamentals for diffusive and connective mass transfer, Radiation laws, heat exchange between black and non black surfaces, Network Analysis, Heat pump refrigeration cycles and systems, Condensers, evaporators and expansion devices and controls, Properties and choice of refrigerant, Refrigeration Systems and components, psychometrics, comfort indices, cooling loading calculations, solar refrigeration.
4. TURBO-MACHINES AND POWER PLANTS: Continuity, momentum and Energy Equations. Adiabatic and Isentropic flow, fanno lines, Rayleigh lines, Theory and design of axial flow turbines and compressors, Flow through turbo-machine blade, cascades, centrifugal compressor. Dimensional analysis and modeling. Selection of site for steam, hydro nuclear and stand-by power plants, Selection base and peak load power plants, Modern High Pressure, High duty boilers, Draft and dust removal equipment, Fuel and cooling water systems, heat balance, station and plant heat rates, operation and maintenance of various power plants, preventive maintenance, economics of power generation.



1

Thermodynamics

1. Basic Concepts, Heat and Work

1.1 Explain why PMMK I and PMMKII devices are not practicable. (Perpetual Motion Machine Kind)
[IFS (Mains) 2002 : 10 Marks]

Solution:

The first law states the principle of conservation of energy. Energy is neither created nor destroyed, but only gets transformed from one form to another. There can be no machine which would continuously supply mechanical work without some other form of energy disappearing simultaneously.

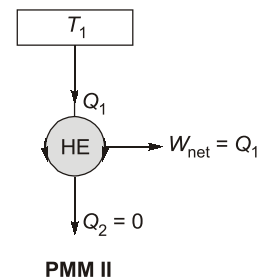
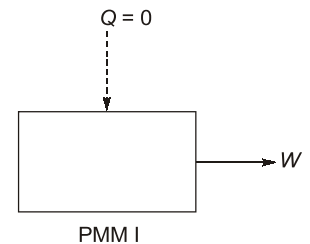
Such fictitious machine is called a perpetual motion machine of the first kind or in brief PMMK I. A PMMK I is thus impossible. The converse of the above statement is also true. There can be no machine which would continuously consume work without some other form of energy appearing simultaneously.

The Kelvin Planck statement of second law states: It is impossible for a heat engine to produce a net work in a complete cycle if it exchanges heat only with single reservoir i.e. not rejecting any heat with lower temperature ($Q_2 = 0$).

Thus,

$$\eta = 1 - \frac{Q_2}{Q_1}$$

and if $Q_2 = 0$ (i.e. $W_{\text{net}} = Q_1$ or $\eta = 100\%$) the heat engine will produce net work in a complete cycle by exchanging heat with only one reservoir, thus violating the Kelvin-Planck statement. Such a heat engine is called a perpetual motion machine of the second kind, PMMK II. A PMMK II is thus impossible.



1.2 State the Zeroth law of thermodynamics and highlight its significance.

[IFS (Mains) 2013 : 5 Marks]

Solution:

When a body A is in thermal equilibrium with a body B , and also separately with a body C , then B and C will be in thermal equilibrium with each other. This is known as Zeroth law of Thermodynamics. It is the basis of temperature measurement.

Significance:

1. It has wide applications in thermometry.
2. If a body C is a thermometer and it is used to measure temperatures of A and B . And if it shows both the readings as same, then (C) is infact showing its own temperature.

1.3 For an isothermal process, show that:

$$\int_1^2 p dV = - \int_1^2 V dp$$

[IFS (Mains) 2013 : 5 Marks]

Solution:

For an isothermal process, to prove:

$$\int_1^2 P dV = -\int_1^2 V dP$$

Isothermal process is defined as, $PV = \text{Constant} = C$

Differentiating both sides, we get,

$$P dV + V dP = 0$$

or

$$P dV = -V dP$$

When system undergoes change in state from state (1) to state (2).

$$\int_1^2 P dV = -\int_1^2 V dP$$

- 1.4 The readings of two thermometers *A* and *B* agree at ice point and steam point as 0°C and 100°C. The two temperature readings are related by the following expression:

$$t_A = a + bt_B + ct_B^2$$

where *a*, *b* and *c* are constants. In a constant temperature bath, the temperature are shown as 51°C on thermometer *A* and 50°C on thermometer *B*. Determine the reading on thermometer *B* when the thermometer *A* reads 65°C. Can you comment which of the two thermometers is correct?

[IFS (Mains) 2016 : 20 Marks]

Solution:

Given: $t_A = a + bt_B + ct_B^2$

As the reading of two thermometers *A* and *B* agree at ice point (0°C) and steam point (100°C).

When

$$t_A = 0^\circ\text{C}, t_B \text{ is also } 0^\circ\text{C}$$

$$= a + bt_B + ct_B^2$$

$$0 = a + b(0) + c(0)^2$$

$$a = 0$$

So,

$$t_A = bt_B + ct_B^2$$

when,

$$t_A = 100^\circ\text{C}, t_B \text{ is also } 100^\circ\text{C}$$

$$100 = b(100) + c(100)^2$$

$$b + (100)c = 1$$

... (i)

when,

$$t_B = 50^\circ\text{C}, t_A = 51^\circ\text{C}$$

$$t_A = bt_B + ct_B^2$$

$$51 = (50)b + (50)^2c$$

... (ii)

From equations (i) and (ii), we get

$$b = 1.04$$

$$c = -4 \times 10^{-4}$$

∴

$$t_A = 1.04 t_B - 4 \times 10^{-4} t_B^2$$

when, t_A reads 65°C

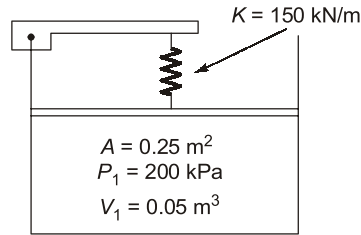
$$65 = 1.04 t_B - 4 \times 10^{-4} t_B^2$$

or

$$t_B = 64.07^\circ\text{C}$$

None of the two thermometers are ideal. So we cannot comment on to which is more correct.

- 1.5 A piston-cylinder device contains 0.05 m³ of a gas initially at 200 kPa. At this state, a linear spring that has a spring constant of 150 kN/m is touching the piston but exerting no force on it. Now heat is transferred to the gas, causing the piston to rise and to compress the spring until the volume inside the cylinder doubles. If the cross-sectional area of the piston is 0.25 m², determine:
- the final pressure inside the cylinder,
 - the total work done by the gas.



[(IFS Mains) 2017 : 10 Marks]

Solution:

Assumptions:

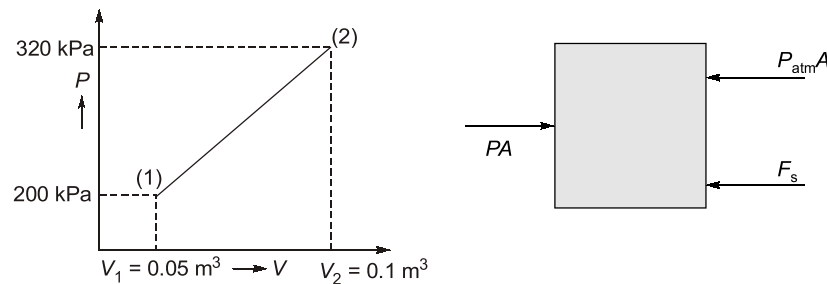
1. Mass conserved in the process.
2. Surrounding conditions are not altered in the process.

Initial volume (V_1) = 0.05 m^3 ,

Initial pressure (P_1) = 200 kPa ,

Spring constant (k) = 150 kN/m , Area $A = 0.25 \text{ m}^2$.

Let the final pressure and volume inside the cylinder be P_2 and V_2 respectively.



At any state,

For initial state,

and

or,

$\Rightarrow$

where,

$$PA = P_{\text{atm}} A + F_s$$

$$F_s = 0$$

$$P_1 = P_{\text{atm}} = 200 \text{ kPa}$$

$$P_2 A = P_1 A + F_s$$

$$P_2 = P_1 + \frac{kx}{A}$$

$$P = F(x) \text{ (linear variations)}$$

$$x = \frac{V_2 - V_1}{A} = \frac{2V_1 - V_1}{A} = \frac{V_1}{A} = \frac{0.05}{0.25} = 0.2 \text{ m}$$

$$P_2 = 200 + \frac{150 \times 0.2}{0.25} = 200 + 120 = 320 \text{ kPa}$$

$$\text{Total work done by the gas, } W = \int_{x_1}^{x_2} P A dx = \int_1^2 P dV = \text{Area under curve 1-2}$$

$$W_{1-2} = \int_{x_1}^{x_2} (P_{\text{atm}} A + kx) dx = 200 \times 0.25 \times 0.2 + \frac{1}{2} \times 150 \times 0.2^2 = 13 \text{ kJ}$$

or,

$$W_{1-2} = \text{area under curve 1-2} = \frac{1}{2} [200 + 320] \times 0.2 \times 0.25 = 13 \text{ kJ}$$

- 1.6 A non-flow quasi-static process occurs for which $P = (-3V + 16)$ bar, where V is the volume in m^3 . What is the work done when V changes from 2m^3 to 6m^3 ?

[(IFS Mains) 2019 : 8 Marks]

Solution:

Given, $P = (-3V + 16)$ bar; $V_1 = 2\text{ m}^3$; $V_2 = 6\text{ m}^3$

Work done in non-flow process,

$$\begin{aligned} W &= \int P dV = \int_{V_1}^{V_2} (-3V + 16) dV = \left[\frac{-3V^2}{2} + 16V \right]_2^6 \\ &= \frac{-3}{2}(6^2 - 2^2) + 16(6 - 2) = -1.5 \times 32 + 16 \times 4 \\ &= 16 \text{ bar} \cdot \text{m}^3 = 16 \times 10^5 \text{ N-m} \end{aligned}$$

Workdone, $W = 1600 \text{ kJ}$

- 1.7 What is the reversible adiabatic work for a steady flow system when KE and PE changes are negligible? How is it different from a closed stationary system?

[(IFS Mains) 2020 : 8 Marks]

Solution:

For a flow system at steady state

From (SFEE)

$$\dot{m} \left[h_1 + \frac{V_1^2}{2000} + gz_1 \right] + \dot{Q} = \dot{m} \left[h_2 + \frac{V_2^2}{2000} + gz_2 \right] + \dot{W}$$

Since,

$$\Delta PE = 0 = \Delta KE$$

$$\dot{Q} = 0 \text{ (adiabatic process)}$$

$$\Rightarrow \dot{m}(h_1 - h_2) = \dot{W} \quad \dots(i)$$

For a closed stationary system

From 1st law of thermodynamics

$$\begin{array}{c} \Delta Q \\ \swarrow \\ \text{(Adiabatic)} \end{array} = \Delta u + \Delta W$$

$$\Rightarrow \dot{W} = (u_1 - u_2) \quad \dots(ii)$$

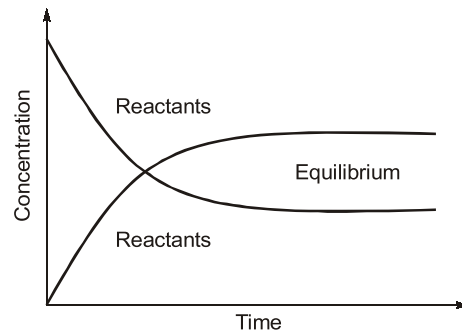
Hence, comparing (i) and (ii), we see that the terms are different w.r.t. enthalpy and internal energy that is to say that the flow work term is absent in closed system.

- 1.8 Explain the term chemical equilibrium. How are equilibrium products of combustion different from non-dissociated species? Also explain the effect of temperature on the equilibrium composition.

[IFS (Mains) 2024 : 8 Marks]

Solution:

Chemical equilibrium is **the thermodynamic equilibrium in a system where direct and reverse chemical reactions are possible**. If chemical equilibrium takes place in the system, the rates of all reactions proceeding in two opposite directions are equal. In a chemical reaction, chemical equilibrium is the state in which both the reactants and products are present in concentrations which have no further tendency to change with time, so that there is no observable change in the properties of the system.



Equilibrium products of combustion are primarily carbon dioxide and water, while non-dissociated species products are dependent on the type of chemical reaction:

Equilibrium products of combustion: The main products of combustion are carbon dioxide and water, along with energy. Combustion occurs when the total heat energy of the reactants equals the total heat energy of the products, which is known as thermal equilibrium.

Non-dissociated species products: Non-dissociated species products depend on the type of chemical reaction. For example, in a weak electrolyte, most of the solute does not dissociate, while in a strong electrolyte, a higher ratio of solute dissociates to form free ions.

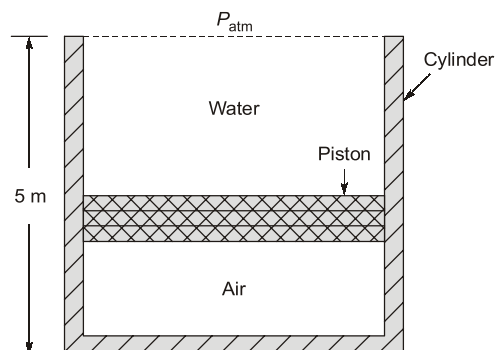
The higher is the temperature, more is the dissociation. However, the effect of dissociation is lower for lean mixtures because the excess oxygen tends to drive the reactions toward completion, and for higher furnace pressure. Thus, the effect of dissociation is not significant in steam generator furnace combustion, which occurs with excess air at about 1500°C .

The effect of temperature on equilibrium change:

- According to Le Chatelier's principle, the equilibrium can be shifted in forward or backward direction by indicating the nature (endothermic or exothermic) of the reaction on changing the temperature.
- In this reaction $A + B \rightleftharpoons C + D$, when the reaction is in forward direction then it will be exothermic reaction while the backward reaction will be endothermic reaction.
- The equilibrium will shift in forward direction by releasing heat on decreasing the temperature of a reaction.

Thus, when the temperature is increased the equilibrium shifts in backward direction.

- 1.9 (i) Consider a spherical balloon is filled from a bottle of helium gas, which is at pressure ' P_H '. If the surface tension of the balloon material is ' S ' and the atmospheric pressure is ' P_o ', establish a relation between P_H , S and P_o as the function of balloon's diameter ' D ' at any given instant of time.
- (ii) A 5 m high cylinder with cross-sectional area of 0.25 m^2 has a massless piston at the bottom with water on top of it, as shown in the figure. Air at 25°C and volume of 0.5 m^3 , under the piston is heated so that the piston moves up, spilling the water out over the side. Find the total heat transfer to the air to push all the water out. Consider the water temperature as 20°C and atmospheric pressure is 1 atm. The density of water can be taken as 998 kg/m^3 .

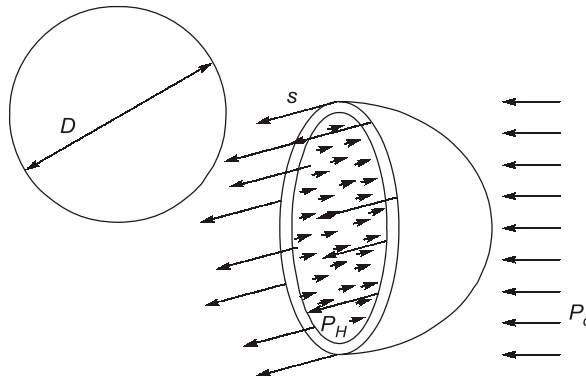


Consider $C_v = 0.718\text{ kJ/kg K}$ and $R = 0.287\text{ kJ/kgK}$ for air.

[IFS (Main) 2025 : 5+10 = 15 Marks]

Solution:

- (i) P_H - Pressure inside Helium balloon
 S - Surface tension of balloon material
 P_o - Atmospheric pressure
 n - Diameter of balloon at any given instant



Force balance on balloon,

$$2S \times \pi D + P_o \times \frac{\pi}{4} D^2 = \left[P_H \times \frac{\pi}{4} D^2 \right]$$

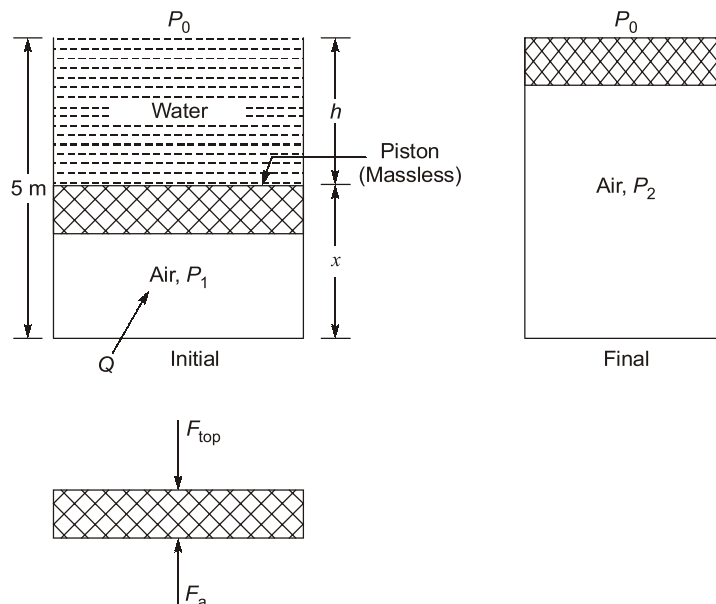
$$(P_H - P_o) \times \frac{D}{4} = 2S$$

$$P_H - P_o = \frac{8S}{D}$$

$$P_H = P_o + \frac{8S}{D}$$

Ans.

- (ii) Given: Area, $A = 0.25 \text{ m}^2$, $T_1 = 25^\circ\text{C}$, $V_1 = 0.5 \text{ m}^3$, $T_w = 20^\circ\text{C}$, $P_{\text{atm}} = P_o = 1 \text{ atm} = 101.3 \text{ kPa}$, $\rho_w = 998 \text{ kg/m}^3$.



Force by air on piston = Force on top of piston

$$P_1 \times A_p = (P_{\text{atm}} + \rho gh) A_p$$

$$P_1 = 101.3 + \frac{998 \times 9.81 \times h}{1000}$$

$$P_1 = 101.3 + 9.79h \quad \dots (i)$$

$\therefore$

$$V_1 = 0.5 \text{ m}^3 = A_{px} \quad [\text{Neglecting thickness of piston}]$$

$$x = \frac{0.5}{0.25} = 2 \text{ m}$$

$$h = 5 - x = 5 - 2 = 3 \text{ m}$$

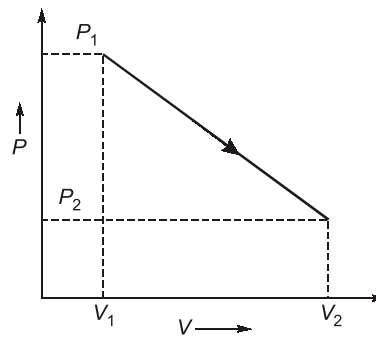
From equation (i),

$$P_1 = 101.3 + 9.79 \times 3 = 130.67 \text{ kPa}$$

When, $h = 0$, $P = P_2$,

$$P_2 = 101.3 \text{ kPa}$$

As piston will rise, water will fall outside the cylinder and pressure of air will decrease linearly as per equation (i)



$$\begin{aligned} V_2 &= \text{Final volume of air} = A \times \text{Total height of cylinder} \\ &= 0.25 \times 5 = 1.25 \text{ m}^3 \end{aligned}$$

Also, for air,

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$$\frac{130.67 \times 0.5}{298} = \frac{101.3 \times 1.25}{T_2}$$

$$T_2 = 577.55 \text{ K}$$

$$m_1 = \frac{P_1 V_1}{R T_1} = \frac{130.67 \times 0.5}{0.287 \times 298} = 0.7639 \text{ kg}$$

Change in internal energy of air,

$$\begin{aligned} \Delta U &= m c_v (T_2 - T_1) \\ &= 0.7639 \times 0.718 \times (577.55 - 298) \\ &= 153.33 \text{ kJ} \end{aligned}$$

Work done by air = Area under PV diagram

$$\begin{aligned} &= \frac{1}{2} \times (P_1 + P_2) \times (V_2 - V_1) \\ &= \frac{1}{2} \times (130.67 + 101.3) \times (1.25 - 0.5) \\ &= 86.988 \text{ kJ} \end{aligned}$$

Using first law of thermodynamics,

$$\begin{aligned} Q &= \Delta U + W = 153.33 + 86.988 \\ &= 240.318 \text{ kJ} \end{aligned}$$

Ans.

2. First Law of Thermodynamics

- 2.1 An insulated rigid chamber of 2.5 m^3 capacity contains air at 25°C and 250 kPa . A paddle wheel inserted in the chamber does 900 kJ of work on the air.

Assuming constant specific heats, calculate the entropy increase during the process.

Take $c = 0.717 \text{ kJ/kg-K}$ and $R = 0.287 \text{ kJ/kg-K}$.

[IFS (Mains) 2001 : 10 Marks]

Solution:

Given: Volume, $V = 2.5 \text{ m}^3$, $T = 25^\circ\text{C} = 298 \text{ K}$,

$P = 250 \text{ kPa}$, Work done by paddle wheel, $W_{\text{paddle}} = 900 \text{ kJ}$

As the chamber is insulated one, the paddle wheel work will increase the internal energy of the liquid.

$$dQ = dU + dW$$

$$dQ = 0,$$

$$\text{and} \quad dW = -900 \text{ kJ} \quad (\text{Work is done on the system})$$

$$dU = 900 \text{ kJ}$$

$$mc_V(T_2 - T_1) = 900 \text{ kJ}$$

$$\text{Also,} \quad PV = mRT$$

$$m = \frac{250 \times 10^3 \times 2.5}{287 \times 298} = 7.3 \text{ kg}$$

$$7.3 \times 0.717 \times (T_2 - 298) = 900$$

$$T_2 = 469.76 \text{ K}$$

$$(\Delta S)_{\text{system}} = \text{Entropy increase of system} = \left[mc_V \ln \frac{T_2}{T_1} + mR \ln \frac{V_2}{V_1} \right]$$

For ideal gas:

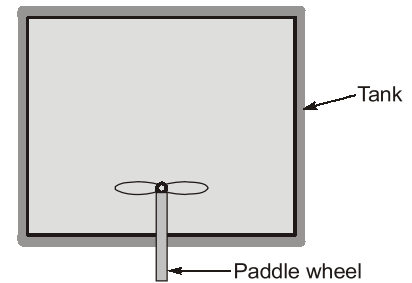
$$[V_2 = V_1] \Rightarrow \text{For constant volume process.}$$

$$= \int_{T_1}^{T_2} \frac{mc_V dT}{T} = mc_V \ln \left(\frac{T_2}{T_1} \right) = 7.3 \times 0.717 \times \ln \left(\frac{469.76}{298} \right) = 2.382 \text{ kJ/K}$$

- 2.2 (i) An ideal gas is heated at constant volume until its temperature is 3 times the original temperature, then it is expanded isothermally till it reaches its original pressure, the gas is then restored to its original state. Determine the expression of net work done.
- (ii) 300 kJ/s of heat is supplied at a constant fixed temperature of 290°C to a heat engine. The heat rejection takes place at 8.5°C . The following results were obtained:
- I. 215 kJ/s of heat is rejected
 - II. 150 kJ/s of heat is rejected
 - III. 75 kJ/s of heat is rejected

Using Clausius inequality which of the results report a reversible cycle of irreversible cycle, or impossible result?

[IFS (Mains) 2003 : $5 + 5 = 10$ Marks]



Solution:

(i) Given: $T_2 = 3T_1$, $T_2 = T_3 = 3T_1$

$$W_{1-2} = 0 \text{ [Constant volume process]}$$

$$W_{2-3} = P_2 V_2 \ln\left(\frac{P_2}{P_3}\right)$$

$$P_2 = 3P_1 \text{ and } P_1 = P_3$$

$$\frac{P_2}{P_3} = 3$$

$$W_{2-3} = P_2 V_2 \ln(3) = 1.098 P_2 V_2 = 1.098 mRT_2$$

$$W_{3-1} = P_1(V_3 - V_1) = mR(T_3 - T_1)$$

$$= mR(3T_1 - T_1) = 2mRT_1 = \frac{2mRT_2}{3} = 0.66 mRT_2$$

$$W_{\text{net}} = W_{1-2} + W_{2-3} + W_{3-1} = 0 + 1.098 mRT_2 - 0.66 mRT_2 = 0.438 mRT_2$$

$$W_{\text{net}} = 1.314 mRT_1$$

(ii) Given: $Q_1 = 300 \text{ kJ/s}$, $T_1 = 290^\circ\text{C} = 563 \text{ K}$, $T_2 = 8.5^\circ\text{C} = 281.5 \text{ K}$

Clausius Inequality says,
$$\oint \frac{dQ}{T} = \frac{Q_1}{T_1} - \frac{Q_2}{T_2}$$

Case I:

$$T_1 = 563 \text{ K}, T_2 = 281.5 \text{ K}$$

When

$$W_2 = 215 \text{ kJ/s}$$

$$\oint \frac{dQ}{T} = \frac{300}{563} - \frac{215}{281.5} = -0.23$$

As

$$\oint \frac{dQ}{T} < 0 \quad (\text{Cycle is possible and irreversible})$$

Case II:

When

$$Q_2 = 150 \text{ kJ/s}$$

$$\oint \frac{dQ}{T} = \frac{Q_1}{T_1} - \frac{Q_2}{T_2} = \frac{300}{563} - \frac{150}{281.5} = 0 \quad (\text{Cycle is reversible})$$

Case III:

When,

$$Q_2 = 75 \text{ kJ/s}$$

$$\oint \frac{dQ}{T} = \frac{Q_1}{T_1} - \frac{Q_2}{T_2} = \frac{300}{563} - \frac{75}{281.5} = 0.266$$

As

$$\oint \frac{dQ}{T} > 0 \quad (\text{Cycle is impossible})$$

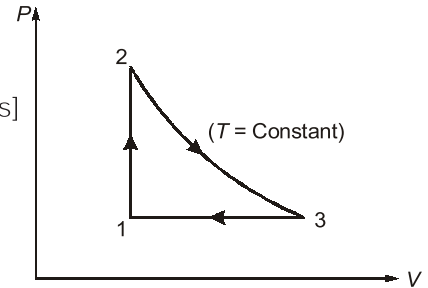
2.3 In a closed system, dry saturated steam at 100 bar expands isothermally and reversibly to a pressure of 10 bar. Calculate the heat supplied and work done per kg of steam during the process.

[IFS (Mains) 2004 : 20 Marks]

Solution:

Give: $P_1 = 100 \text{ bar}$ (dry saturated steam), $P_2 = 10 \text{ bar}$

Expansion is isothermal and reversible,



From steam table,

At

$$P_1 = 100 \text{ bar (saturated steam)}$$

$$T_1 = 311.06^\circ\text{C}$$

$$u_1 = 2544.4 \text{ kJ/kg}$$

$$h_1 = 2724.7 \text{ kJ/kg}$$

$$v_1 = v_g = 0.018026 \text{ m}^3/\text{kg}$$

As the expansion process is isothermal.

$$T_1 = T_2 = 311.06^\circ\text{C}$$

and

$$P_2 = 10 \text{ bar}$$

$$T_{\text{sat}} = 179.91^\circ\text{C}$$

$\therefore (T_2 > T_{\text{sat}}) \rightarrow$ (It is in superheated state)

From steam table,

At, $T_{300^\circ\text{C}}$, $u_{300^\circ\text{C}} = 2793.2 \text{ kJ/kg}$

At, $T_{350^\circ\text{C}}$, $u_{350^\circ\text{C}} = 2875.2 \text{ kJ/kg}$

Using linear interpolation, method,

$$u_2 - 2793.2 = \frac{2875.2 - 2793.2}{350 - 300} (311.06 - 300)$$

$$u_2 = 2811.3384 \text{ kJ/kg}$$

Similarly,

$$(v_2 - 0.25794) = \frac{0.28247 - 0.25794}{350 - 300} (311.06 - 300)$$

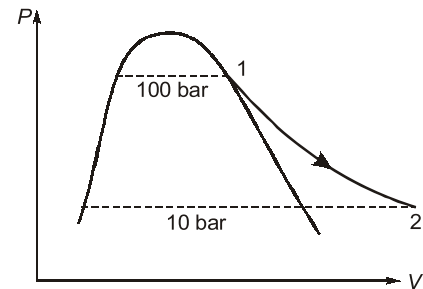
$$v_2 = 0.2633 \text{ m}^3/\text{kg}$$

$$\text{Work done per kg, } w = P_1 v_1 \ln\left(\frac{P_1}{P_2}\right) = (100 \times 10^5) \times (0.018026) \ln\left(\frac{100}{10}\right) = 415.063 \text{ kJ/kg}$$

and

$$u_2 - u_1 = 2811.3384 - 2544.4 = 266.9384 \text{ kJ/kg}$$

$$\text{Heat supplied per kg, } Q = (u_2 - u_1) + w = 266.9384 + 415.063 = 682.0014 \text{ kJ/kg}$$



- 2.4 (i) An inventor claims to have developed an engine which draws 1000 kJ of heat energy per cycle each from two thermal reservoirs at temperatures 1500 K and 900 K and rejects 1600 kJ of heat energy per cycle to a thermal reservoir at 300 K while performing 400 kJ per cycle of work. Examine the validity of the claim using first law of thermodynamics and inequality of Clausius.
- (ii) Using appropriate T-ds relations, show that the slope of the constant volume line is higher than that of a constant pressure line passing through a given state represented on a temperature-entropy diagram for a perfect gas. Sketch the temperature-entropy diagram.

[IFS (Mains) 2006 : 5 + 5 = 10 Marks]

Solution:

(i) Given: $Q_1 = 1000 \text{ kJ}$, $Q_2 = 1600 \text{ kJ}$

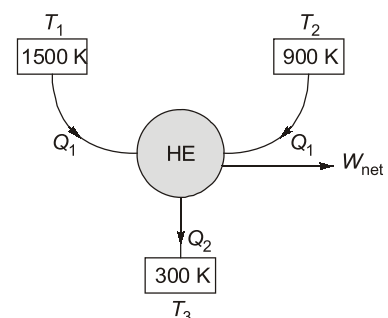
$$\text{Work, } W_{\text{given}} = 400 \text{ kJ (Given)}$$

Using 1st law of thermodynamics, work produced in a cycle

$$\oint_c \sigma Q = \oint_c \sigma W$$

$$W_{\text{net}} = 2Q_1 - Q_2$$

$$= 2 \times 1000 - 1600 = 400 \text{ kJ} = W (\text{given})$$



It satisfy the 1st law of thermodynamics.

According to clausius inequality.

$$\oint \frac{\delta Q}{T} = \frac{Q_1}{T_1} + \frac{Q_1}{T_2} - \frac{Q_2}{T_3} = \frac{1000}{1500} + \frac{1000}{900} - \frac{1600}{300} = 0.66 + 1.11 - 5.33 = -3.5633$$

As $\oint \frac{\delta Q}{T} < 0$

[The cycle is possible and irreversible in nature]

(ii) Using Tds relations, $Tds = c_V dT + T \left(\frac{\partial P}{\partial T} \right)_V dV$

At constant volume, $dV = 0$

$$(Tds)_V = (c_V dT)_V$$

$$\left(\frac{\partial T}{\partial s} \right)_V = \frac{T}{c_V}$$

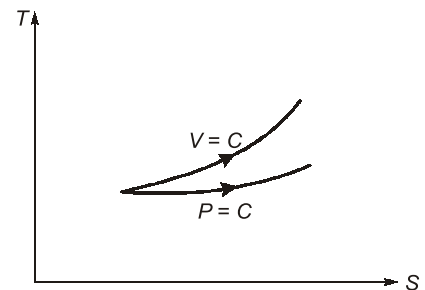
Similarly, $Tds = c_P dT - T \left(\frac{\partial V}{\partial T} \right)_P dP$

At constant pressure, $dP = 0$

$$\left(\frac{\partial T}{\partial s} \right)_P = \frac{T}{c_P}$$

As $(c_P > c_V \text{ or } \gamma > 1)$ $\left(\frac{\partial T}{\partial s} \right)_V > \left(\frac{\partial T}{\partial s} \right)_P$

The slope of constant volume line is higher than that of constant pressure line passing through a given state represented on a temperature - entropy diagram.



- 2.5 A closed cylinder of 0.25 m diameter is fitted with a light frictionless piston. The piston is retained in position by a catch in the cylinder wall and the volume on one side of the piston contains air at a pressure of 750 kN/m². The volume on the other side of the piston is evacuated. A helical spring is mounted co-axially with the cylinder in this evacuated space to give a force of 120 N on the piston in this position. The catch is released and the piston travels along the cylinder until it comes to rest after a stroke of 1.2 m. The piston is then held in its position of maximum travel by a ratchet mechanism. The spring force increases linearly with the piston displacement to a final value of 5 kN. Calculate the work done by the compressed air on the piston.

[IFS (Mains) 2008 : 15 Marks]

Solution:

Assumptions:

1. Only conservative forces
2. No leakage
3. Insulated piston.

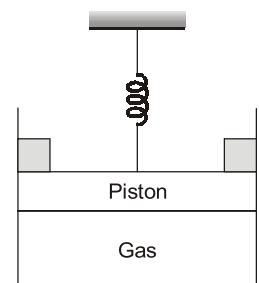
Given: $d = 0.25$ m, $A_P = \text{Area of piston} = \frac{\pi}{4} d^2$, $A_P = \frac{\pi}{4} (0.25)^2 = 0.049$ m²

Initial Position

$$(P_g)_1 = 750 \text{ kN/m}^2$$

$$(F_g)_1 = (P_g)_1 \times A_P = 750 \times 0.049 = 36.79 \text{ kN}$$

x_1 is initial compression of spring, $kx_1 = f_{s1} = 120$ N



Final position: Let x_2 be the final compression in spring.

$$x_2 - x_1 = 1.2 \text{ m} \quad (\text{Given})$$

$$kx_2 = f_{S2} = 5 \text{ kN} = 5000 \text{ N}$$

Since,

$$x_2 - x_1 = 1.2$$

$$\frac{5000}{k} - \frac{120}{k} = 1.2$$

$$k = \text{Spring stiffness} = 4066.67 \text{ N/m}$$

and

$$kx_1 = 120$$

$$x_1 = \frac{120}{4066.67} = 0.029 \text{ m}$$

and

$$kx_2 = 5000 \text{ N}$$

$$x_2 = \frac{5000}{4066.67} = 1.229 \text{ m}$$

Neglecting piston weight and friction.

So, work done by the compressed air on the piston,

$$\begin{aligned} W &= F_S dx = \int_{x_1}^{x_2} kx dx \\ &= k \frac{x^2}{2} \Big|_{x_1}^{x_2} = \frac{k}{2} (x_2^2 - x_1^2) = \frac{4066.67}{2} [1.229^2 - 0.029^2] = 3.07 \text{ kJ} \end{aligned}$$

2.6 Consequent upon first law of thermodynamics, show that the heat is a path function.

[IFS (Mains) 2010 : 7 Marks]

Solution:

The amount of work (W) done by the system when it undergoes change in state from (i) to (ii) in a reversible process in closed system is given as

$$W_{1-2} = \int_{V_1}^{V_2} P dV$$

Thus the magnitude of the work done is given by the area under the path 1-2. Since the area under each curve represents the work for each process, the amount of work involved in each case is not a function of the end states of the process, and thus it depends on the path the system follows in going from state 1 to state 2. For this reason work is called a path function.

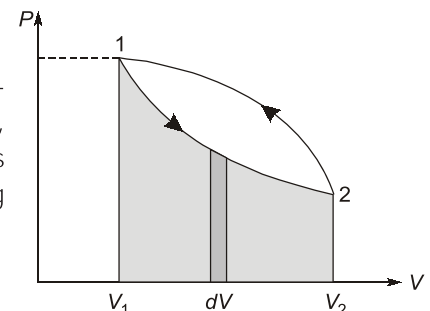
According to first law of thermodynamics,

$$dU = \delta Q - \delta W$$

Consider a system undergoes a cyclic process. Its initial and final states are same. And as internal energy is a property of system ($U_1 - U_1$) or ($dU = 0$).

$$\Rightarrow \oint_c \delta Q = \oint_c \delta W$$

As work transfer is a path function. The heat transfer (δQ) like (δW), also depends on the process and is path-dependent and not a property.



2.7 In a system executing a non-flow process the work and heat per degree change of temperature are

given by $\frac{dW}{dT} = 200 \text{ W} \cdot \text{s}/^\circ\text{C}$ and $\frac{dQ}{dT} = 160 \text{ J}/^\circ\text{C}$

What will be the change in internal energy of the system when its temperature changes from $T_1 = 55^\circ\text{C}$ to $T_2 = 95^\circ\text{C}$?

[IFS (Mains) 2013 : 5 Marks]