



ZONE TECH
Best Institute For Assistant & Junior Engineer

RPSC-AEn Mains

Work Book Solution

for

Thermodynamics



Visit Our Website
www.zonetech.in



DOWNLOAD NOW

<https://zonetech.in/downloads>

PART - A

2 Marks Questions

1.
Sol. This law states that the specific heat of a gas is the same at constant pressure. It does not depend on the value of pressure. Regnault's law is also known as Gay Lussac's law. This law states that the pressure of a given mass of a gas is directly proportional to its absolute temperature at constant volume.
$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$
2.
Sol. Conservation of energy, basically energy cannot be created or destroyed, only converted.
3.
Sol. Entropy in a given system must always increase. If I were to provide an example, let's picture a cube of ice. Consider all of the particles in the cube of ice. If the cube of ice were to melt and remelt, the particles in the cube of ice would not be arranged in the same manner. This is because entropy is always increasing. Entropy is another word for disorganization.
4.
Sol. Entropy of a given system approaches an absolute value as its temperature approaches zero, meaning that the disorganization becomes finite.
5.
Sol. The Rankine cycle is a 4 process cycle where you take your working fluid, water, pump it up, then add heat from the boiler. Once the fluid gets heated, it turns into steam, which drives the turbine to generate work. Upon exit of the turbine, the working fluid goes through a condenser, and the cycle continues again.
6.
Sol. Efficiency is what you get over that you pay. What we get is the work generated from the turbine, what we pay is for the heat that goes into the boiler.
7.
Sol. The Otto Cycle is the ideal thermodynamic cycle describing the function of a spark ignited piston engine.
8.
Sol. The diesel cycle is also a thermodynamic cycle that describes a combustion engine. Fuel is ignited by heat generated during air compression into the combustion chamber.
9.
Sol. The Otto Cycle, being more ideal is more efficient. However, the diesel engine would be more efficient at high compression ratio applications.
10.
Sol. Carnot cycle, Otto cycle, Diesel cycle, Dual cycle, Brayton cycle, Atkinson cycle, Stirling cycle.
11.
Sol. Mean effective pressure is defined as the constant pressure acting on the piston during.
12.
Sol. 1. It consists of two isentropic, one constant volume and one constant pressure processes.



2. Heat is rejected at constant volume.
3. Used in diesel engines.

13.

Sol. Inside the turbine the gas is continuously flowing in the processes are flow processes are flow processes. Since all the processes involved in Brayton cycle is flow process, it has been used as the cycle for gas turbine.

14.

Sol. In closed cycle gas turbine, the same working fluid is recirculated again and again.

15.

Sol. In open cycle gas turbine, the exhaust gas from turbine is exhausted to the atmosphere and fresh air is taken in compressor for every cycle.

16.

Sol. By providing inter cooler, re-heater along with heat exchanges.

17.

Sol. The intercooler is placed between L.P. and H.P. compressors. It is used to cool the gas coming from L.P. compressor to its original temperature.

18.

Sol. The expansion process is very often performed in two separate turbine stages. The re-heater is placed between the H.P. and L.P. turbines to increase the enthalpy of the exhaust gas coming from H.P. turbine.

Effects:

1. Turbine output is increased for the same compression ratio.
2. Thermal efficiency is less.

19.

Sol. The main function of heat regenerator is to exchange the heat from exhaust gas to the compressed air for preheating before combustion chamber. It increases fuel economy and thermal efficiency.

20.

Sol. The Brayton cycle is a thermodynamic cycle that describes the process of air compression, fuel combustion, and expansion to produce mechanical work. In gas turbines, this cycle is fundamental, as it represents the sequence of events with the engine, where air is compressed, mixed with fuel and ignited, and then expanded to produce thrust or power.

21.

Sol. It is a fixed mass or a region in space (controlled volume) where our study is focused.

22.

Sol. There are three types of thermodynamic system.

1. Closed System
2. Open System
3. Isolated System

Types of System	Exchange of Energy	Exchange of Mass	Example
1. Closed System	✓	✗	IC engine without valve.
2. Open System	✓	✓	Piston cylinder with valves turbine, pump
3. Isolated System	✗	✗	Perfectly Insulated Thermos

23.

Sol. 1. **Intensive Property (Intrinsic):-** Intensive property is Independent of mass of system under consideration.

Ex:- Pressure, temperature, density, conductivity, specific energy, velocity and all specific properties.

2. **Extensive Property (Extrinsic):-** Extensive property depends on the mass of system under consideration.

Ex:- Volume, Energy, Entropy, etc.

24.

Sol. The variables which are independent of the path followed by the system.

Ex:- Pressure, Temperature, volume, etc.

The variables which depends on the past history of the system.

Ex:- Heat and work.

25.

Sol. A system consisting of a single phase is called homogeneous system.

Ex:- Ice, water, dry saturated steam.

26.

Sol. A system is said to be in thermodynamic equilibrium if it satisfied the following equilibrium.

(a) **Thermal Equilibrium:-** (Means equality of temperature) It is condition or state in which the temperature of the system is uniform.

(b) **Mechanical Equilibrium:-** Equality of forces i.e. pressure at any point should not change with time (It may or may not be uniform). It is condition or state in which there is no unbalanced force within the system and nor at its boundaries.

(c) **Chemical Equilibrium:-** No chemical reaction potential should be present. Means equality of chemical potential. Chemical equilibrium represents that condition or state of the system when all chemical reactions in it have ceased and there is no mass diffusion.

(d) **Phase Equilibrium:-** Mass of each phase should remain constant with time.

27.

Sol. The change in the state of the system is called as process.

28.

Sol. **Reversible process:-** A process is said to be reversible in which system returns to its original state without leaving any effect on the surrounding.

Irreversible Process:- A process is irreversible if the system passes through a sequence of non-equilibrium states. During such a process, the properties of the system do not have a unique value.

29.

Sol. It is a substance of constant chemical composition throughout its volume of mixture irrespective of phase.

Ex:- Gaseous mixture of O_2 and N_2

30.

Sol. According to Gibbs Phase Rule

$$P + F = C + 2$$

where

P = Number of phases (Liquid, gas, solid)

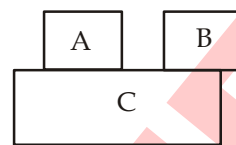
C = Number of chemical component

F = Degree of Freedom

31.

Sol. It gives the concept of temperature.

According to zeroth law of Thermodynamics. If a body A is in thermal equilibrium with body C and if a body B is separately in thermal equilibrium with body C then A and B are also in thermal equilibrium with each other.



$$T_A = T_C$$

$$T_B = T_C$$

So $T_A = T_B$

32.

Sol. The variable property with the help of which temperature is measured, known as thermometric property. Thermometers are based on finding thermometric property.

33.

Sol. There are six types of thermometers:-

1. Resistance thermometer or Thermistor
2. Thermocouple Thermometer
3. Constant volume gas thermometer
4. Constant Pressure gas thermometer
5. Ordinary Thermometer
6. Ideal Gas Thermometer

34.

Sol. $PV = n\bar{R}T$

where

n = Number of moles = Mass / Molecular weight



$\bar{R}$ = Universal gas constant (8.314 kJ/kg Mole-K)

35.

Sol. A gas behaves as an ideal gas under low pressure and high temperature condition.

36.

Sol. In case of constant volume process the complete heat is utilised in increasing the temperature of gas molecules whereas in case of constant pressure process some part of the heat is used in the increasing the temperature and some part of the heat is utilised in doing some work.

37.

Sol. $PV^n = C$

Process	n
1. Isothermal Process	$n = 1$
2. Adiabatic Process	$n = \gamma$
3. Isobaric Process	$n = 0$
4. Isochoric Process	$n = \infty$

38.

Sol. According to Joule's law heat is proportional work.

$$W \propto Q$$

$$W = JQ \quad \Rightarrow \quad J = \frac{W}{Q}$$

J = Mechanical Equivalence of heat

If $Q = 1$ Kcal. then

$$J = W$$

It means requirement of Joule work in any system for producing 1 Kcal heat is called mechanical equivalence of heat.

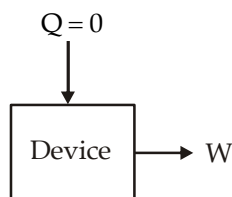
39.

Sol. It is the property of a thermodynamics system which represents total heat content of the system. It is denoted by H.

$$H = U + PV$$

40.

Sol. Perpetual motion machine 1 is a hypothetical device which develops work continuously without absorbing energy from outside.



It violates first law of thermodynamics.

41.

Sol. For real gases, enthalpy is a function of both temperature and pressure whereas for ideal gases, enthalpy depends on only temperature.



42.

Sol. In the polytropic process, specific heat is negative which leads to decrease in temperature when heat is supplied.

43.

Sol. Relationship between specific heat at constant pressure, constant volume and characteristic gas constant is given by the Mayer's relation.

$$C_p - C_v = R$$

where

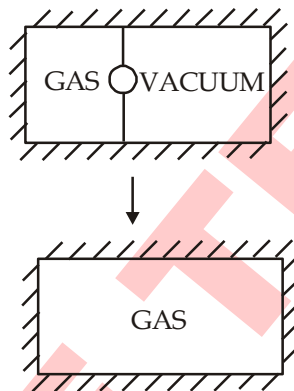
C_p = Specific heat at constant pressure

C_v = Specific heat at constant volume

R = Characteristic gas constant

44.

Sol. Expansion of a gas against vacuum is known as free expansion.



45.

Sol. Flow through a restricted passage partially opened valve, venturimeter, porous plug is known as throttling. Throttling is known as constant enthalpy or isenthalpic process.

46.

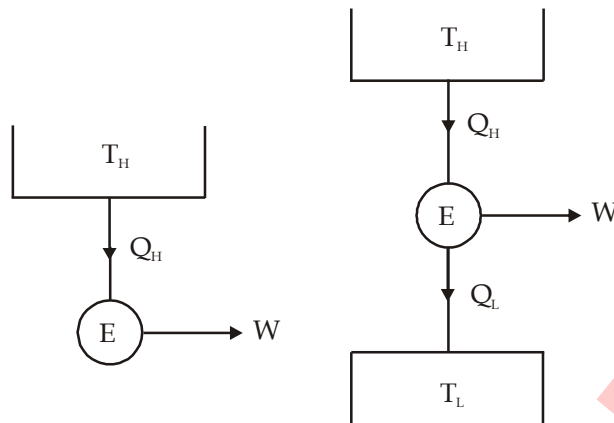
Sol. Any form of energy transfer is called work except the energy transfer due to temperature difference. Heat is known as low grade energy whereas work is known as high grade energy.

47.

Sol. A reservoir of infinite heat capacity is known as thermal energy reservoir.
Ex:- Evaporator and Condenser

48.

Sol. It is impossible to construct a device operating in a cycle producing work while interacting with a single thermal reservoir.



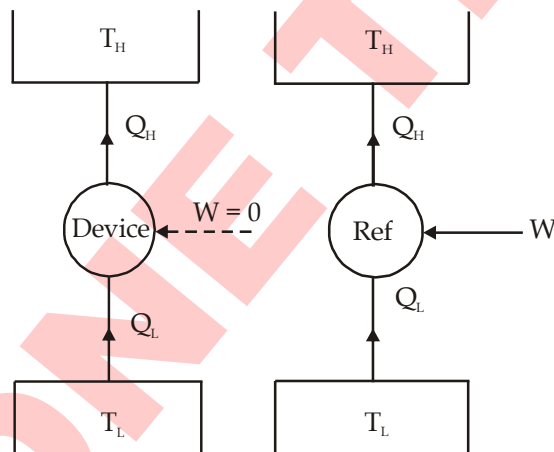
(Non-possible)

(Possible)

It provides the concept of work producing devices.

49.

Sol. It is impossible to construct a device operating in a cycle transfers heat from low temperature reservoir to high temperature reservoir without consuming any other form of energy.



(Not possible)

(Possible)

It provides the concept of work absorbing devices.

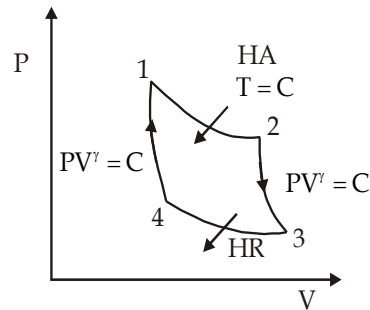
50.

Sol. The devices which produce work are called as power producing devices like that turbine whereas those devices which consume work for their operation like that pump are known as power absorbing devices.

51.

Sol. There are four process used in Carnot cycle in which two process are isothermal and two are adiabatic process.





Process 1-2 → Reversible isothermal heat addition process

Process 2-3 → Reversible adiabatic expansion process

Process 3-4 → Reversible isothermal heat rejection process

Process 4-1 → Reversible adiabatic compression process

52.

Sol. It is the most efficient cycle because all the process that are used in Carnot cycle are completely reversible process i.e. carnot cycle is internally as well as externally reversible cycle.

53.

Sol. According to this if two engines are working at same temperature limit, the efficiency of these engine can never be greater than the Carnot/Reversible cycle.

$$\eta_{\text{Reversible}} > \eta_{\text{Irreversible}}$$

54.

Sol. According to clausius, cyclic integral of $\oint \frac{\delta Q}{T}$ is always less than or equal to zero.

$$\oint \frac{\delta Q}{T} \leq 0$$

$$\oint \frac{\delta Q}{T} < 0 \rightarrow \text{Irreversible cycle}$$

$$\oint \frac{\delta Q}{T} = 0 \rightarrow \text{Reversible cycle}$$

$$\oint \frac{\delta Q}{T} > 0 \rightarrow \text{Impossible cycle}$$

55.

Sol. It is the measurement of degree of disorderness or randomness of the molecules. It is the extensive property.

56.

Sol. The maximum work that can be obtained in cycle process is known as Available energy.

57.

Sol. The minimum energy that is rejected to sink is known as Unavailable energy.

58.

Sol. Gibbs function is given by

$$G = H - TS$$

Change in Gibbs function represents maximum useful work in open system.

59.

Sol. According to this theorem the rate of irreversibility is directly proportional to the rate of entropy generation of universe.

$$I \propto (ds)$$

$$I = T_0 (ds)_{\text{universe}}$$

$$(ds)_{\text{universe}} = (ds)_{\text{system}} + (ds)_{\text{surrounding}}$$

60.

Sol. **Key Characteristics of PMM-II:**

Concept: A machine that runs in a complete cycle, takes heat from only one heat source (reservoir), and produces net work.

Violation: It contradicts the Kelvin-Planck statement, which says you must reject some heat to a colder sink for a heat engine to operate.

Efficiency: Theoretically 100% (all heat into work), but practically impossible due to the Second Law.

Distinction from PMM-I: PMM-I (First Kind) violates the First Law (no energy input, continuous work), while PMM-II violates the Second Law (no heat rejection).

61.

Sol. It represents the deviation the actual gas with respect to the ideal gas for ideal gas in value of Z is equal to 1 whereas for real gas it may be less than 1 or greater than 1.

$$Z = \frac{PV}{RT}$$

62.

Sol.

- A binary vapour cycle is a combination of two cycles, one in a high-temperature region and the other in a lower temperature region
- In the binary cycle (two-fluid), two cycles with different working fluids are coupled in series.
- The heat rejected by one being utilized by another cycle; So, the overall efficiency of the plant increases

63.

Sol. The four basic components of a steam power plant are:

1. **Boiler/steam generator:** This is where water is heated and converted into high-pressure steam by burning fuel (like, coal, natural gas, or oil).

2. **Turbine:** The high-pressure steam from the boiler expands through the turbine, causing it to rotate. This rotational energy is then used to drive a generator.

3. **Generator:** Connected to the turbine, the generator converts the mechanical energy of the rotating turbine into electrical energy.

4. **Condenser:** After passing through the turbine, the steam is condensed back into water in the condenser. This water is then returned to the boiler to be reheated, completing the cycle.

64.

Sol. Given that,

$$\Delta T = 400 - 200$$

$$\Delta T = 200^\circ\text{F}$$

We have the Formula,

$$R_h = W_s \times c \times \Delta T$$

$$R_h = 500 \times 0.48 \times 200$$

That equals, $R_h = 48000 \text{ btu/hr}$



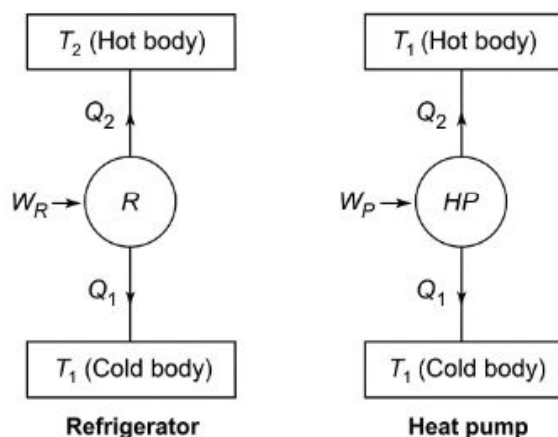
PART - B

5 Marks Questions

65.

Sol. The performance of a refrigerator is expressed by the ratio of amount of heat taken from the cold body (Q_1) to the amount of work required to be done on the system (W_R). This ratio is called coefficient of performance.

Whereas, the performance of a heat pump is expressed by the ratio of the amount of heat delivered to the hot body (Q_2) to the amount of work required to be done on the system (W_p). This ratio is called coefficient of performance or energy performance ratio of a heat pump.



Mathematically, coefficient of performance of refrigerator can be written as,

$$(\text{COP})_R = \frac{Q_1}{W_R} = \frac{Q_1}{Q_2 - Q_1}$$

And, coefficient of performance of heat pump,

$$(\text{COP})_{HP} = \frac{Q_2}{W_p} = \frac{Q_2}{Q_2 - Q_1}$$

$$(\text{COP})_{HP} = \frac{Q_2 + Q_1 - Q_1}{Q_2 - Q_1}$$

$$(\text{COP})_{HP} = \frac{(Q_2 + Q_1) + Q_1}{(Q_2 - Q_1)} = 1 + \frac{Q_1}{Q_2 - Q_1}$$

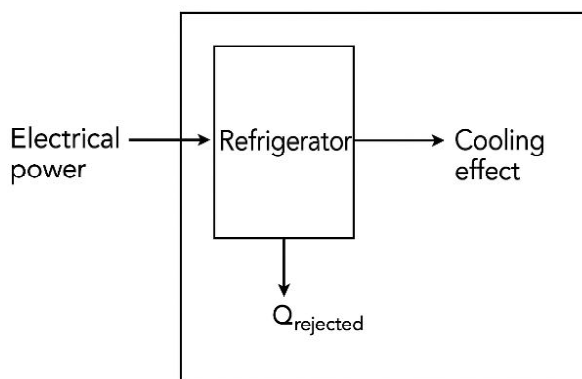
$$(\text{COP})_{HP} = 1 + (\text{COP})_R \quad [\text{From equation (i)}]$$

From above we can see that COP of refrigerator may be less than one or greater than one depending on the type of refrigeration system used.

But the COP of a heat pump is always greater than COP of refrigerator.

66.

Ans.



Refrigerator Inside the insulated room

Considering the kitchen room with the refrigerator to be a thermodynamic system. Since it is insulated and all doors and windows are closed, the only heat interaction is in the form of electrical energy which is being given for operating the refrigerator.

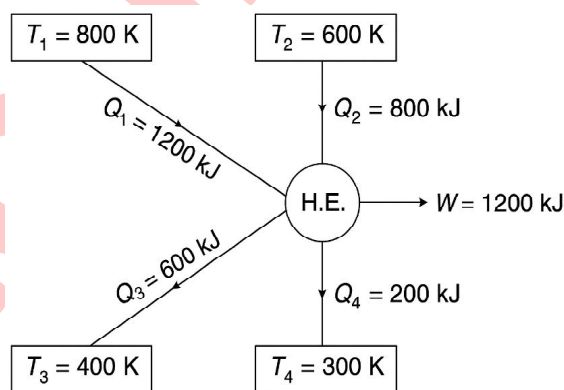
To produce the cooling effect inside the refrigerator, this electrical energy is utilized and at the same time, the refrigerator must reject some heat to the kitchen (which acts as high temperature reservoir). Thus, after some time, the housewife feels uncomfortable due to this heat which is rejected into the kitchen room as it causes a rise in temperature.

67.

Sol. According to Clausius inequality, we have

$$\oint \frac{\delta Q}{T} \leq 0$$

$$\frac{Q_1}{T_1} + \frac{Q_2}{T_2} - \frac{Q_3}{T_3} - \frac{Q_4}{T_4} \leq 0$$



Heat engine

$$\frac{1200}{800} + \frac{800}{600} - \frac{600}{400} - \frac{200}{300} \leq 0$$

$$1.5 + 1.33 - 1.5 - 0.66 \leq 0$$

$$0.67 \leq 0$$

That is, $\oint \frac{\delta Q}{T} > 0$.

It means the heat engine is impossible.



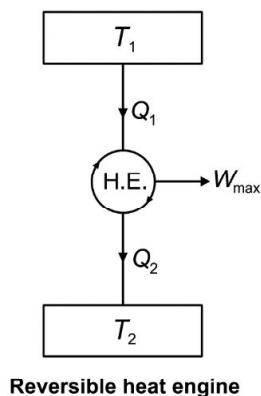
68.

Sol. Given data:

$$T_1 = 550^\circ\text{C} = (550 + 273) \text{ K} = 823 \text{ K},$$

$$T_2 = 25^\circ\text{C} = (25 + 273) \text{ K} = 298 \text{ K},$$

$$Q_1 = 1200 \text{ kJ/min}$$



For maximum output,

$$\eta = 1 - \frac{T_2}{T_1}, \quad \text{also } \eta = \frac{W_{\max}}{Q_1}$$

$$1 - \frac{T_2}{T_1} = \frac{W_{\max}}{Q_1}$$

$$1 - \frac{298}{823} = \frac{W_{\max}}{1200}$$

$$1 - 0.3620 = \frac{W_{\max}}{1200}$$

$$0.638 = \frac{W_{\max}}{1200}$$

or

$$W_{\max} = 0.638 \times 1200 = 765.6 \text{ kJ/min.}$$

$$= \frac{765.6}{60} \text{ kJ/s} = \mathbf{12.76 \text{ kW}}$$

69.

Sol. The Carnot cycle cannot be considered as the theoretical cycle for steam power plants due to following reasons:

Boiler: Isothermal heat transfer eliminates the possibility of using sub-cooled liquid boiler feed or producing superheated vapour in the boiler.

Turbine: Adiabatic expansion yields low steam quality in the turbine feed. This can result in damage to the turbine rotor.

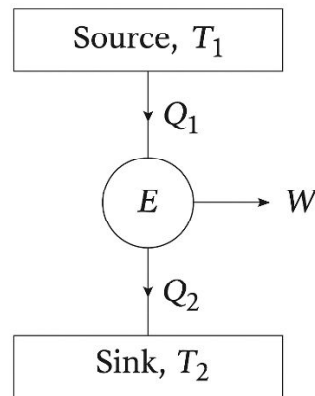
Condenser: Isothermal heat transfer eliminates the possibility of using superheated vapour in the condenser feed. It is impossible to design a condenser to give exit conditions in wet region.

Pump: Quality > 0 in the pump feed. This can result in damage to the pump rotor. If the condenser is designed and operated to produce a saturated liquid effluent, isentropic pump will yield a sub-cooled liquid at the pressure of the boiler. This will make it impossible to operate the boiler isothermally.

$$\eta = 0.4 = 1 - \frac{T_2}{T_1}$$



$$\frac{T_2}{T_1} = 0.6$$



$$T_1' = 1.1 \times T_1 \text{ (New high temperature)}$$

$$\eta_{\text{new}} = 1 - \frac{T_2}{T_1'} = 1 - \frac{T_2}{1.1 \times T_1} = 1 - \frac{1}{1.1} \times \frac{T_2}{T_1} = 1 - \frac{0.6}{1.1} = \frac{0.5}{1.1}$$

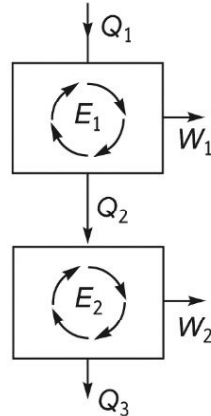
$$= 0.4545 = 45.45\%$$

70.

Sol. We know that,

$$\eta_1 = 1 - \frac{Q_2}{Q_1} \text{ and } \eta_2 = 1 - \frac{Q_3}{Q_2}$$

$$Q_1 = \frac{Q_2}{1 - \eta_1} \quad Q_3 = (1 - \eta_2) Q_2$$



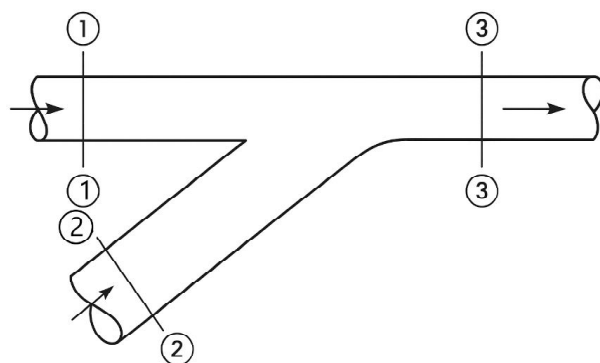
For combined cycle,

$$\eta = 1 - \frac{Q_3}{Q_1} = 1 - \frac{(1 - \eta_2) Q_2}{\frac{Q_2}{(1 - \eta_1)}}$$

$$\eta = 1 - (1 - \eta_1)(1 - \eta_2) = \eta_1 + \eta_2 - \eta_1 \eta_2$$

71.

Sol. Given: Cold water: m_1 4 kg, $T_1 = 40^\circ\text{C}$ ($40+273$) K = 313 KHot water: $m_2 = 6$ kg, $T_2 = 100^\circ\text{C}$ ($100+273$) K = 373 K



(i) Let

T_3 = Temperature of mixture

$m_3 = m_1 + m_2$, mass of mixture water = 4 + 6 = 10 kg

Applying the energy balance equation, we get

$$m_1 h_1 + m_2 h_2 = m_3 h_3$$

$$m_1 C_p T_1 + m_2 C_p T_2 = m_3 C_p T_3$$

or

$$m_1 T_1 + m_2 T_2 = m_3 T_3$$

$$4 \times 313 + 6 \times 373 = 10 \times T_3$$

or

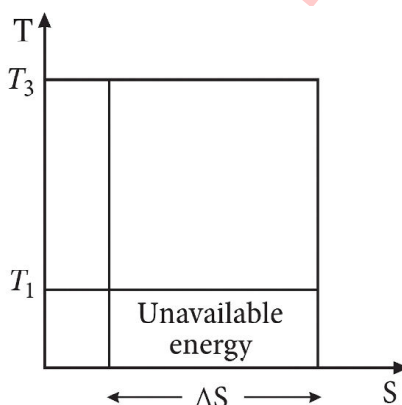
$$T_3 = 349 \text{ K}$$

72.

Sol. At 40°C, for water

$$(\Delta S)_w = m_1 c_p \log_e \frac{T_3}{T_1} = 4 \times 4.18 \log_e \frac{349}{313}$$

$$= 1.82 \text{ kJ/K}$$



Assume atmospheric temperature, $T_0 = 300 \text{ K}$

$\therefore$ Unavailable energy = $T_0 (\Delta S)_w = 300 \times 1.82 = 546 \text{ kJ}$

73.

Sol.

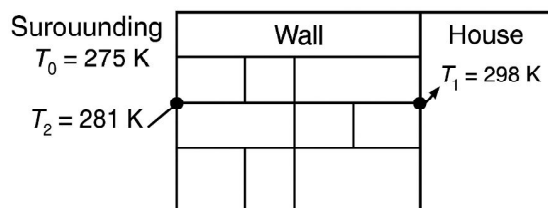
Given: Ambient temperature, $T_0 = 275 \text{ K}$;

Heat lost by house, $Q = 30 \text{ kJ/min} = 500 \text{ W}$

Inner surface temperature of wall, $T_1 = 25^\circ\text{C} = 298 \text{ K}$;

Outer surface temperature of wall,

$T_2 = 8^\circ\text{C} = 281 \text{ K}$



Entropy generation within wall,

$$S_{\text{gen}} = \frac{Q}{T_2} - \frac{Q}{T_1} \quad [\text{Given steady state conditions}]$$

$$= \frac{500}{281} - \frac{500}{298} = 0.1015 \text{ W / K}$$

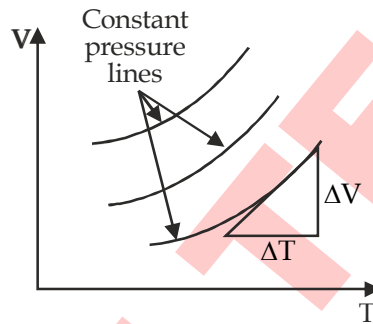
The rate of energy distruction within the walls is given by

$$(i)_{\text{wall}} = T_o S_{\text{gen}} = 275 \times 0.1015 = 27.91 \text{ W}$$

74.

Sol. Coefficient of cubical expansion (β):

- When experimental results of p-V-T measurement are plotted keeping pressure constant, the slope of the constant pressure lines on V-T graph are $\left(\frac{\partial V}{\partial T}\right)_p$.
- If this gradient is divided by the volume at that state we get a property β .



$$\therefore \beta = \frac{1}{V} \left(\frac{\partial V}{\partial T} \right)_p$$

75.

Sol. If entropy is imagined as a function of T and P then, $S = f(T, p)$

$$dS = \left(\frac{\partial S}{\partial T} \right)_p dT + \left(\frac{\partial S}{\partial P} \right)_T dp \quad \dots(i)$$

Multiply with T, $TdS = T \left(\frac{\partial S}{\partial T} \right)_p dT + T \left(\frac{\partial S}{\partial P} \right)_T dp$

$$\left. \begin{array}{l} \text{Since } T \left(\frac{\partial S}{\partial P} \right)_p = C_p \\ \text{and } \left(\frac{\partial S}{\partial P} \right)_T = - \left(\frac{\partial V}{\partial T} \right)_p \end{array} \right\} \begin{array}{l} \text{Putting in (i)} \\ \text{(from fourth Maxwell relation)} \end{array}$$

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

If S is constant $dS = 0$

$$\therefore C_p (dT)_s = T \left(\frac{\partial V}{\partial T} \right)_p (dp)_s$$

$$C_p = T \left(\frac{\partial V}{\partial T} \right)_p \left(\frac{\partial p}{\partial T} \right)_s$$

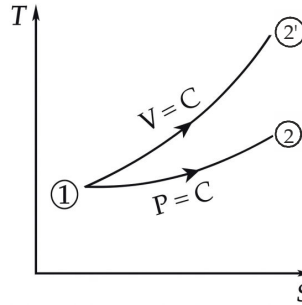


76.

Sol. Writing the two TdS equations

$$TdS = C_p dT - T \left(\frac{\partial V}{\partial T} \right)_p dp \quad \dots(i)$$

$$TdS = C_v dT + T \left(\frac{\partial p}{\partial T} \right)_v dV \quad \dots(ii)$$



At constant pressure Eq. (i) reduces to

$$T(dS)_p = C_p(dT)_p - 0$$

$$\Rightarrow \left(\frac{\partial T}{\partial S} \right)_p = \frac{T}{C_p} \quad (\text{slope of constant pressure line on T-s diagram})$$

At constant volume Eq. (ii) reduces to

$$T(dS)_v = C_v(dT)_v$$

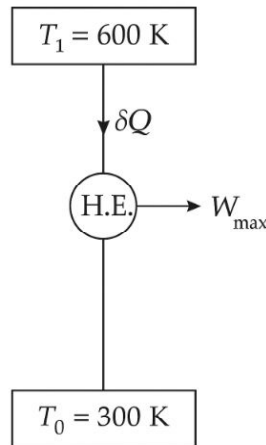
$$\Rightarrow \left(\frac{\partial T}{\partial S} \right)_v = \frac{T}{C_v} \quad (\text{slope of constant volume line on T-s diagram})$$

$$\frac{(\partial T / \partial S)_v}{(\partial T / \partial S)_p} = \frac{C_p}{C_v} \text{ as } C_p > C_v \Rightarrow \frac{C_p}{C_v} > 1 \Rightarrow \left(\frac{\partial T}{\partial S} \right)_v > \left(\frac{\partial T}{\partial S} \right)_p$$

77.

Sol. Considering kinetic and potential energy changes are negligible. The reversible i.e. maximum work can be calculated by considering a reversible engine between source and sink.

$$W_{\text{rev}} = \int_{T_1}^{T_0} \left(1 - \frac{T_0}{T} \right) \delta Q$$



Source is rejecting heat to sink.

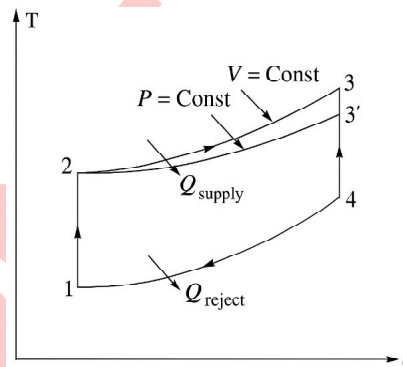
$$\therefore \delta Q = cdT = 0.04T^2 dT$$

$$W_{rev} = \int_{600}^{300} \left(1 - \frac{300}{T} \right) + (0.04T^2 dT) = \int_{300}^{600} (0.04T^2 - 300 \times 0.04T) dT$$

$$= \frac{0.04}{3} (T^3)_{300}^{600} - \frac{300 \times 0.04}{2} (T^2)_{300}^{600} = 900000 \text{ J}$$

$$= 900 \text{ kJ}$$

78.
Sol.



Here, cycle 1-2-3-4-1 is Otto cycle and cycle 1-2-3'-4-1 is diesel cycle.

$$\text{As, } \eta_{\text{engine}} = \frac{\text{Work done}}{Q_{\text{supply}}} \text{ or } \frac{W}{Q_s} = \frac{W}{W + Q_R} = \frac{1}{1 + \frac{Q_R}{W}} \quad \dots(i)$$

Heat rejected (Q_R) for Otto and Diesel cycle is same.

From T-s diagram it can clearly seen that

$W_{\text{Otto}} > W_{\text{Diesel}}$ by area 2-3'-3-2

From equation (i) we can see that with increasing W , denominator value decreases and hence inefficiency increases,

So, $\eta_{\text{Otto}} > \eta_{\text{Diesel}}$

79.
Sol.

- Air is the working substance.
- Throughout the cycle, air behaves as a perfect gas and obeys all the gas laws.
- No chemical reaction takes place in the cylinder

- d. Both expansion and compression are strictly isentropic
- e. The values of specific heats of the air remain constant throughout the cycle.

80.

Sol. Otto Cycle & Diesel Cycle

1. Otto cycle consist of two adiabatic and two constant volume process.
2. It consists of two adiabatic, one constant volume and one constant pressure processes.
3. Compression ratio is equal to expansion ratio
4. Compression ratio is greater than expansion ratio.
5. Heat addition takes place at constant volume.
6. Heat addition takes place at constant pressure
7. Compression ratio is less. It is varies from 6 to 8.

81.

Sol. "A regenerator in a gas turbine can enhance fuel efficiency by recovering heat from the exhaust gases and preheating the incoming air. This process reduces fuel consumption. However, the addition of a regenerator introduces complexity and may lead to increased maintenance requirements."

82.

Sol. "Combined cycle power plants integrate gas turbines and steam turbines to maximize energy output. The combination of these cycles results in higher overall efficiency compared to standalone systems. Additionally, combined cycle plants offer lower environmental impact, with reduced emissions."

83.

Sol. "Compressor efficiency is crucial in a gas turbine engine as it directly affects the overall efficiency of the entire system. A more efficient compressor ensures higher pressure ratios, leading to improved combustion and ultimately higher power output. It plays a key role in determining the overall performance and fuel efficiency of the gas turbine."

84.

Sol. "Inlet air cooling involves lowering the temperature of the incoming air before it enters the gas turbine. This process enhances the air density, resulting in increased power output and improved efficiency. It's especially beneficial in hot climates where high ambient temperatures can negatively impact gas turbine performance."

85.

Sol. The Carnot cycle is not practicable for a steam power plant for several reasons, primarily due to the ideal and reversible nature of its processes, which are difficult to achieve in real-world applications:

- **Isothermal Heat Addition and Rejection:** Achieving truly isothermal heat addition and rejection in a steam power plant is practically impossible. Heat addition would require a constant temperature source and sink, which is hard to maintain during phase changes in a real boiler or condenser.
- **Isentropic Compression and Expansion:** The isentropic (reversible adiabatic) compression of a wet vapor mixture is very difficult to achieve in practice. It would require a compressor that can handle a two-phase mixture without friction or heat loss, which is not feasible. Similarly, isentropic expansion in a turbine is also challenging due to friction and heat transfer losses.
- **Low Efficiency at Practical Temperatures:** While the Carnot cycle provides the maximum possible efficiency between two given temperatures, the practical temperature limits of steam power plants (due to material limitations and safety concerns) would result in a relatively low Carnot efficiency that might not be economically viable.
- **Difficulty in Maintaining Reversibility:** All processes in the Carnot cycle are assumed to be reversible, meaning no losses due to friction, heat transfer across a finite temperature difference, or mixing. In reality, these irreversibilities are unavoidable in any practical power plant.

86.

Sol. The mean temperature of heat addition (T_m) in a Rankine cycle represents the average temperature at which heat is supplied to the working fluid (water/steam) during the heat addition process.

Explanation for Rankine Cycle:

1. Heat Addition Process:

In an ideal Rankine cycle, heat is added to the working fluid in two main stages:

- **Boiler (Constant Pressure):** Water is heated to its saturation temperature, then converted into saturated steam, and finally, often superheated steam at a constant pressure.

- **Superheater (if applicable):** Further heating of the steam above its saturation temperature.
- 2. **Significance of Mean Temperature:**
 - The mean temperature of heat addition is a crucial parameter in determining the thermal efficiency of the Rankine cycle.
 - Higher T_m leads to higher efficiency: According to the Carnot principle, the efficiency of a heat engine increases with an increase in the average temperature at which heat is added and a decrease in the average temperature at which heat is rejected.
- 3. **Calculation:** While it's a mean value, it's not a simple arithmetic average, especially when phase changes occur. It's effectively the temperature that, if heat were added isothermally at that temperature, would result in the same thermal efficiency as the actual heat addition process in the cycle.

87.

Sol.

- **High Temperatures in Turbines:** Gas turbines operate with extremely high inlet temperatures to maximize efficiency. However, these high temperatures can put significant stress on the turbine blades.
- **Creep:** At elevated temperatures, turbine blade materials can experience creep, which is the tendency of a solid material to deform permanently under the influence of persistent mechanical stresses, even below the material's yield strength.
- **Material Degradation:** High temperatures can also cause other forms of material degradation, such as oxidation, corrosion, and microstructural changes, which can weaken the blades and reduce their ability to withstand stress.
- **Metallurgical Limit Definition:** The metallurgical limit is the temperature at which these degradation processes become significant enough to cause the turbine blades to fail or lose their structural integrity.
- **Balancing Efficiency and Reliability:** Engineers must carefully balance the desire for high turbine inlet temperatures (which increase efficiency) with the metallurgical limits of the materials used.
- **Cooling Systems:** To overcome the metallurgical limit, advanced cooling systems are employed to keep turbine blade temperatures below the critical threshold while still allowing for high operating temperatures.

88.

1. The specific output
2. The cycle efficiency
3. Steam rate, and
4. Heat rate of a steam power plant?

Sol.

Reheating in a steam power plant improves both specific output and cycle efficiency while decreasing the steam rate and heat rate. This is achieved by increasing the average temperature of heat addition and reducing moisture content in the low-pressure stages of the turbine.

- (a) **Specific Output:** Reheating increases the net work output of the turbine, thereby increasing the overall specific output (work done per unit mass of steam).
- (b) **Cycle Efficiency:** By reheating the steam, the average temperature at which heat is added to the cycle increases. This leads to a higher thermal efficiency.
- (c) **Steam Rate:** Reheating increases the overall work output of the turbine which means that for the same power output, a lower mass flow rate of steam is required, thus decreasing the steam rate.
- (d) **Heat Rate:** The heat rate is inversely proportional to the cycle efficiency, meaning that as the efficiency increases (due to reheating), the heat rate decreases. A lower heat rate implies that less heat input is required to produce a unit of power.

89.

Sol.

Regeneration in a steam power plant improves efficiency and reduces heat rate by preheating feedwater, which increases the mean temperature of heat addition. However, it can decrease specific output (work done per unit mass of steam) due to steam extraction for feedwater heating. This impacts the steam rate (mass flow rate of steam) and heat rate.

- (a) **Specific Output (Turbine Work):** Regeneration generally decreases specific output. While it



increases efficiency, it does so by bleeding off some steam from the turbine for feedwater heating. This reduces the mass flow rate of steam through the low-pressure stages of the turbine, thus lowering the total work produced.

(b) Mean Temperature of Heat Addition: Regeneration increases the mean temperature of heat addition. By preheating the feedwater with extracted steam, the temperature at which heat is added to the working fluid in the boiler increases, leading to improved efficiency.

(c) Cycle Efficiency: Regeneration increases the cycle efficiency. By preheating the feedwater, less heat needs to be added to the water in the boiler for the same temperature rise, thus increasing overall efficiency.

(d) Steam Rate: Regeneration increases the steam rate (mass flow rate of steam). Although some steam is extracted for feedwater heating, the overall steam flow to the condenser and turbine is increased due to the increased heat input to the boiler to compensate for the heating of the feedwater, resulting in a higher steam rate.

(e) Heat Rate: Regeneration decreases the heat rate. Since regeneration increases cycle efficiency, it means that less heat needs to be added to the system to produce the same amount of work. This leads to a lower heat rate.

90.

Sol. A binary vapor cycle is a thermodynamic cycle that combines two Rankine cycles, each using a different working fluid, to improve overall efficiency.

It utilizes a high-temperature cycle with one fluid and a low-temperature cycle with another, where the heat rejected from the first cycle is used as input for the second.

This arrangement allows for better utilization of heat and can lead to higher overall efficiency compared to using a single Rankine cycle.

Example: Mercury-Steam Binary Cycle

A common example is the mercury-steam binary cycle. Here, mercury vapor expands in a mercury turbine, and the heat released during mercury condensation is used to generate steam, which then drives a steam turbine.

Benefits:

- **Increased Efficiency:** By utilizing the heat rejected from the high-temperature cycle, the overall efficiency of the power plant is improved,
- **Higher Power Output:** The binary cycle can generate more power compared to a single Rankine cycle for the same heat input.
- **Suitable for Geothermal Applications:** Binary cycles are particularly useful in geothermal power plants, where lower-temperature geothermal fluids can be utilized more effectively.

Limitations:

- **Complexity:** Binary cycle systems are more complex than single-cycle systems due to the additional components and the need for two working fluids.
- **Cost:** The higher complexity can also lead to increased capital costs.

91.

Sol. **Rankine Cycle:**

- **In a Topping Cycle:** The Rankine cycle can be the topping cycle itself if the fuel is used to produce steam directly for the turbine.
- **In a Bottoming Cycle:** The Rankine cycle is frequently used as the bottoming cycle to utilize the waste heat from another process.

92.

Sol. **Given data:**

$$T_1 = 30^\circ\text{C} = 303\text{K},$$

$$T_3 = 800^\circ\text{C} \text{ KJ/kg}$$



$$P = 100 \text{ KW},$$

$$C_p = 1 \text{ KJ/kgK},$$

$$\gamma = 1.4$$

For maximum net work done:

$$T_4 = T_2 = \sqrt{T_1 \times T_3} = \sqrt{1073 \times 303} = 570.2 \text{ K}$$

Net work done

$$W_{\text{net}} = C_p [(T_3 - T_4) - (T_2 - T_1)] = 235.6 \text{ KJ / kg}$$

Total power development

$$P = m_a \times W_{\text{net}} = 100/235.6 = 0.4244 \text{ kg/sec}$$

Heat supply to the system:

$$m_f \times C_v = m_a \times C_p \times (T_3 - T_2)$$

$$m_f = [m_a \times C_p \times (T_3 - T_2)] / C_v = 0.4244 \times 1 (1073 - 570.2) / 45.000 = 4.742 \times 10^{-3} \text{ kg/s}$$

93.

Sol. $(W_{\text{net}})_{\text{max}} = c_p (\sqrt{T_{\text{max}}} - \sqrt{T_{\text{min}}})^2$

$$= 1.005 (\sqrt{1073} - \sqrt{300})^2$$

$$= 1.005 (15.43)^2 = 239.28 \text{ kJ / kg}$$

$$\eta_{\text{cycle}} = 1 - \frac{1}{(r_p)^{(\gamma-1)/\gamma}} = 1 - \sqrt{\frac{T_{\text{min}}}{T_{\text{max}}}}$$

$$= 1 - \sqrt{\frac{300}{1073}} = 0.47 \text{ or } 47\%$$

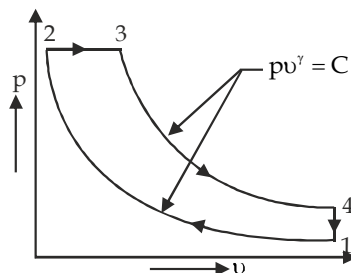
$$\eta_{\text{Carnot}} = 1 - \frac{T_{\text{min}}}{T_{\text{max}}} = 1 - \frac{300}{1073} = 0.721 \text{ or } 72.1\%$$

$$\eta_{\text{relative}} = \frac{\eta_{\text{Brayton}}}{\eta_{\text{Carnot}}} = \frac{0.47}{0.721} = 0.652$$

94.

Sol. From fig.

$$r_k = \frac{v_1}{v_2} = 14$$



$$\begin{aligned}
 v_3 - v_2 &= 0.06(v_1 - v_2) \\
 &= 0.06(14v_2 - v_2) \\
 &= 0.78v_2 \\
 v_3 &= 1.78v_2
 \end{aligned}$$

$$\therefore \text{Cut off ratio, } r_c = \frac{v_1}{v_2} = 1.78$$

$$\begin{aligned}
 \eta_{\text{Diesel}} &= 1 - \frac{1}{\gamma} \cdot \frac{1}{r_k^{\gamma-1}} \cdot \frac{r_c^\gamma - 1}{r_c - 1} \\
 &= 1 - \frac{1}{14} \cdot \frac{1}{(14)^{0.4}} \cdot \frac{(1.78)^{1.7} - 1}{1.78 - 1} \\
 &= 1 - 0.248 \cdot \frac{1.24}{0.78} = 0.605, \text{ i.e. } 60.5\%
 \end{aligned}$$

95.

Sol. Propulsive efficiency (η_p)

- The propulsive efficiency is the fraction of total mechanical power output that is imparted to the working fluid and converted to the thrust power (as opposed to how much is wasted).
- For jet propulsion engines (turbojet and turbofan engines), the total mechanical power output is simply the rate of increase in kinetic energy of the working fluid (jet), also known as the jet power ($\dot{W}_{\text{jet}}$).

For jet propulsion engine

$$\eta_p = \frac{\text{thrust power}}{\text{total power}} = \frac{\dot{W}_F}{\dot{W}_{\text{jet}}} = \frac{\dot{W}_F}{\frac{1}{2} \dot{m}_{\text{air}} (V_e^2 - V_o^2)}$$

where $\dot{W}_F$ = thrust power, V_e = exit velocity, V_o = entrance velocity, $\dot{m}_{\text{air}}$ = mass flow rate of air
 $\therefore$ For jet propulsion engine,

$$\eta_p \propto \dot{W}_F \text{ and } \eta_p \propto \frac{1}{\dot{m}_{\text{air}}}$$

PART - C

20 Marks Questions

96.

Sol. Definition of Enthalpy :

- Enthalpy is significant because it tells us how much heat is there in a system (energy). Heat is essential because it allows us to produce useful work.
- The heat absorbed or released during a process at constant pressure is equal to the change in enthalpy.
- Enthalpy H can be written as,

$$H = U + pV$$

Where,

H = Enthalpy of the system
 U = Internal energy of the system
 p = Pressure of the system
 V = Volume of the system

Enthalpy of an ideal gas depend only on temperature :

Explanation :

Enthalpy of a substance is defined as :

$$h = u + pv$$

According to the First Law of Thermodynamics for a process

$$\delta Q = du + \delta W$$

$$\delta Q = du + p.dV \quad [\text{Process involving just } pdV \text{ work}]$$

At constant pressure,

$$p.dV = d(pV)$$

$$(\delta Q)_p = du + d(pV)$$

$$(\delta Q)_p = d(u + pV)$$

$$(\delta Q)_p = dh$$

i.e., heat transferred at constant pressure increases the enthalpy of the system.

$$h = u + pV$$

$\therefore$

$$h = u + RT$$

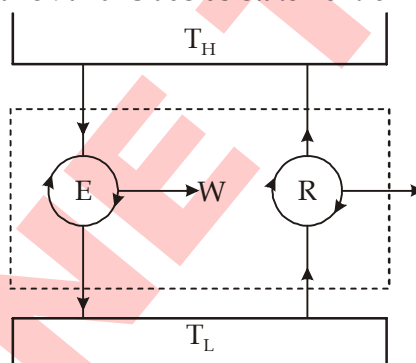
The internal energy (u) of an ideal gas is a function of temperature i.e. $u = f(T)$

Since there are no intermolecular forces of attraction and repulsion

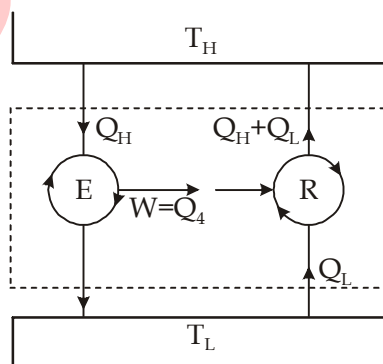
$\therefore$ The enthalpy of an ideal gas also depends on the temperature i.e. $h = f(T)$

97.

Sol. Interdependency of Kelvin-planck and Clausius statement of 2nd law of thermodynamics.



If the Kelvin statement is violated, then no heat is transferred to the lower surrounding, then



If we compare the two and check, then in refrigerator, heat is extracted and transferred to the upper temperature reserve from lower reservoir by an amount

$$Q_H + Q_L - Q_L = Q_{\text{tvm}}$$

So, the heat transfer from lower to higher without-any work-supply.

Thus, violation of Kelvin-planck automatically violates, Clausius statement.



98.

Sol. The following P-V diagram can be sketched with the help of data given in the problem.

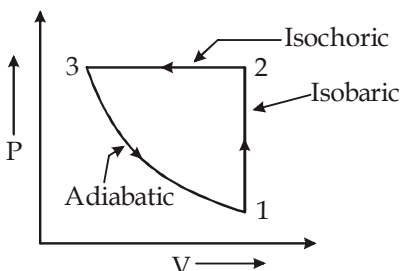
Given,

$$Q_{1-2} = +80 \text{ kJ}$$

$$Q_{2-3} = -85 \text{ kJ} \quad \{\text{as rejected by system} \therefore \text{negative}\}$$

$$Q_{2-3} = -15 \text{ kJ} \quad \{\text{as workdone on the system} \therefore \text{negative}\}$$

$$U_1 = 100 \text{ kJ}$$



Assumptions :

(i) Closed system

(ii) Reversible process

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

$\therefore$ For process 1 - 2 (Isochoric)

According to first law, $Q_{1-2} = \Delta U_{1-2} + W_{1-2}$

But $W_{1-2} = 0$ (as constant volume)

$\therefore$

$$Q_{1-2} = \Delta U_{1-2}$$

$$80 = U_2 - U_1$$

or

$$U_2 = 80 + U_1 = 80 + 100 = 180 \text{ kJ}$$

For process 2 - 3 (isobaric)

According to first law, $Q_{2-3} = \Delta U_{2-3} + W_{2-3}$

$$-85 = (U_3 - U_2) + (-15)$$

$$U_3 - U_2 = 70$$

$$U_3 = -70 + 180 = 110 \text{ kJ}$$

For process 3 - 1 (adiabatic),

$$Q_{3-1} = 0$$

According to first law, $Q_{3-1} = \Delta U_{3-1} + W_{3-1}$

$$0 = (U_1 - U_3) + W_{3-1}$$

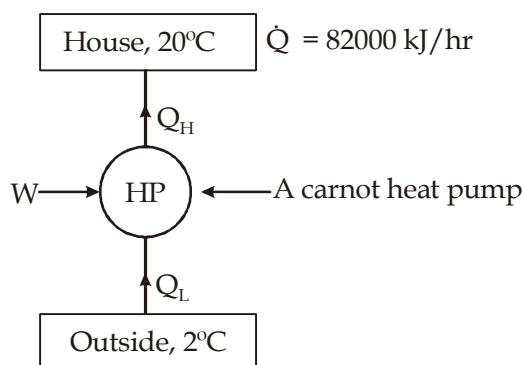
or

$$W_{3-1} = U_3 - U_1$$

$$W_{3-1} = 110 - 100 = 10 \text{ kJ}$$

99.

Sol. Refer to the given figure



Given,

(i) Temperature of the house,



$$T_H = 20^\circ\text{C} = 293 \text{ K}$$

(ii) Temperature outside of the house,

$$T_L = 2^\circ\text{C} = 275 \text{ K}$$

(iii) Rate of heat loss from house,

$$\dot{Q}_H = 82000 \text{ kJ/hr}$$

($\dot{Q}_H = \dot{Q}$ to maintain house at 20°C)

Power required,

$$\dot{W} = 8 \text{ kW}$$

As it is a carnot heat pump

$$\text{COP}_{\text{HP}} = \frac{T_H}{T_H - T_L} = \frac{293}{293 - 275} = 16.28$$

The amount of heat lost is one day

$$Q_H = \dot{Q}_H \times 24 \text{ hrs}$$

$$= 82000 \times 24 = 1968000 \text{ kJ}$$

Thus the required work input to this carnot heat pump can be determined from the definition of COP.

$$\text{COP}_{\text{HP}} = \frac{Q_H}{W}$$

$\therefore$

$$W = \frac{Q_H}{\text{COP}_{\text{HP}}} = \frac{1968000}{16.28} = 120901 \text{ kJ}$$

Thus the length of time, the heat pump ran that day

$$At = \frac{W}{\dot{W}} = \frac{120901}{8} = 15112.63 \text{ s} = 4.2 \text{ hrs}$$

The total heating cost can be found as

$$\text{cost} = W \times \text{price}$$

$$= \dot{W} \times \Delta t \times \text{price}$$

$$= 8 \times 4.2 \times 8 = ₹268.8$$

(as unit of price is per kWh)

If the resistance heating were used, the entire heating load for that day would have to be met by electrical energy.

$\therefore$

$$\text{New cost} = Q_H \times \text{price}$$

$$= 1968000 \times \frac{1 \text{ kWh}}{3600 \text{ kJ}} \times 8 = ₹4373.33$$

$\therefore$ Clearly economically its much better to use a heat pump than an electrical heater.

100.

Sol.

With the help of P-V and T-S diagrams describe diesel cycle.

In diesel cycle there are 4 process

(i) Compression

(ii) Heat Addition

(iii) Expansion

(iv) Heat Rejection

(i) **Compression: Process 1 - 2 :**

Cycle compression process is isentropic process i.e. $PV^\gamma = C$

(ii) **Heat Addition : Process 2 - 3:**

Heat addition takes place at constant pressure. point '3' is known as cut off point.

(iii) **Expansion process : Process 3 - 4 :**

Expansion is isentropic $PV^\gamma = C$

Power output is obtained by this process.

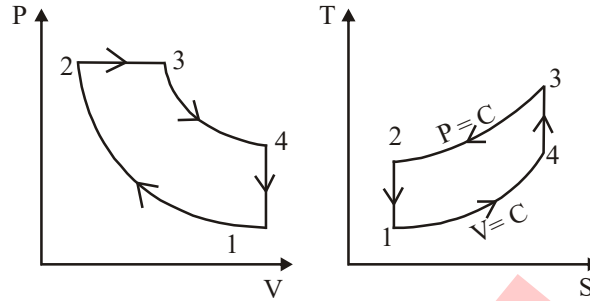
(iv) **Heat rejection process : Process 4 - 1:**

After expansion process heat rejection process takes place. Heat rejection occurs at const. volume.

After completion of above 4 process a cycle is completed.



Efficiency of Diesel Cycle :



$$\eta = 1 - \frac{\text{Heat Rejection}}{\text{Heat Addition}}$$

$$= 1 - \frac{mC_v(T_4 - T_1)}{mC_p(T_3 - T_2)}$$

$$= 1 - \frac{1(T_4 - T_1)}{\gamma(T_3 - T_2)}$$

$$\frac{V_1}{V_2} = r \text{ (comp. ratio)}$$

$$\frac{V_3}{V_2} = \rho, \text{ cut of ratio}$$

$$\frac{V_4}{V_3} = \frac{V_1}{V_3} \text{ Expansion ratio}$$

$$\frac{V_1}{V_3} = \frac{V_1}{V_2} \times \frac{V_2}{V_3}$$

$$\frac{V_1}{V_3} = r \times \frac{1}{\rho} \Rightarrow \text{Exp. ratio} = \frac{r}{\rho}$$

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1}$$

$$T_2 = T_1(r)^{\gamma-1} \quad \dots(i)$$

$$\frac{T_3}{T_2} = \frac{V_3}{V_2}$$

$$T_3 = \rho \cdot T_2 \quad \dots(ii)$$

$$\frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{\gamma-1}$$

$$T_4 = \rho \cdot T_2 \left(\frac{\rho}{r}\right)^{\gamma-1} \quad \left(\because \frac{V_3}{V_1} = \frac{V_3}{V_1} = \frac{\rho}{r}\right)$$

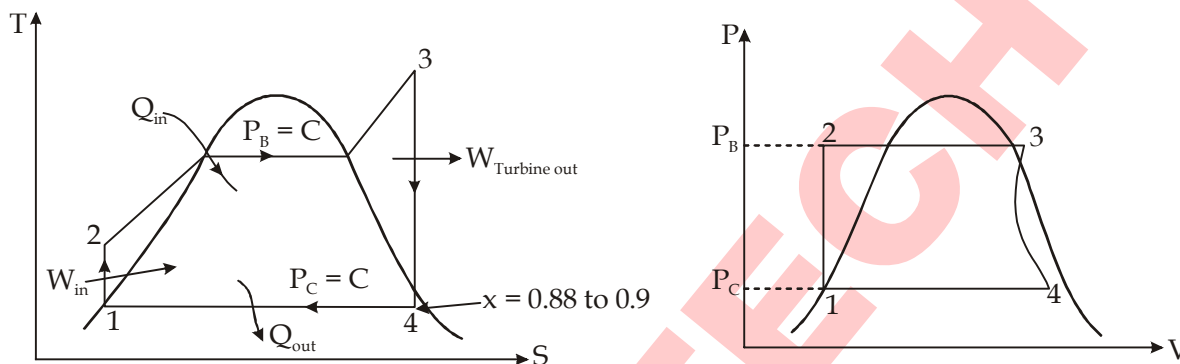
$$= \rho \cdot T_1(r)^{\gamma-1} \left(\frac{\rho}{r}\right)^{\gamma-1}$$

$$= T_1 \rho^\gamma \quad \dots(iii)$$

$$\eta = 1 - \frac{1}{\gamma} \frac{[T_1 \rho^\gamma - T_1]}{[T_1 r^{\gamma-1} \rho - T_1 r^{\gamma-1}]}$$

$$\eta_p = 1 - \frac{1}{\gamma} \frac{(\rho^\gamma - 1)}{r^{\gamma-1} (\rho - 1)}$$

101.
Sol.



T-S and P-V diagram of Rankine cycle

Rankine cycle is the practical working cycle for thermal power plant and it consists of following 4 processes :

(i) **1 - 2 Process**

Reversible adiabatic compression of liquid from condenser to boiler pressure in boiler feed pump.

(ii) **2 - 3 Process**

Constant pressure heat addition process in the boiler to convert liquid into superheated region.

(iii) **3 - 4 Process :**

Reversible adiabatic expansion in the turbine from boiler to condenser pressure.

(iv) **4 - 1 Process :**

Constant pressure heat rejection process in the condenser to get saturated liquid.

- Water enters the pump at state 1 as saturated liquid and is compressed isentropically to the operating pressure of the boiler. The water temperature increases somewhat during this isentropic compression process due to slight decrease in the specific volume of water.
- Water enters the boilers as compressed liquid at state 2 and leaves as a saturated vapour at state 3. The boiler is basically a large heat exchanger where the heat originating from combustion gases, nuclear reactors, or other sources is transferred to the water essentially at constant pressure.
- The superheated vapour at state 3 enters the turbine where it expands isentropically and produces work by rotating the shaft connected to an electric generator. The pressure and temperature drop during this process to the values at state 4, where steam enters the condenser. At this state, steam is usually a standard liquid vapour mixture with a high quality. Steam is condensed at constant pressure in the condenser, which is basically a large heat exchanger. The area under 4 - 1 process on T-S curve represents heat rejected in the condenser.

$$W_T = h_3 - h_4$$

$$W_P = h_2 - h_1$$

$$Q_S = h_3 - h_2$$

$$Q_R = h_4 - h_1$$

$$\eta = \frac{W_{net}}{Q_S} = \frac{W_T - W_P}{Q_S} = \frac{Q_S - Q_R}{Q_S}$$

$$\eta_{\text{Rankine}} = \frac{(h_3 - h_2) - (h_4 - h_1)}{(h_3 - h_2)}$$

102.

Sol. (i) A system will be in a state of thermodynamic equilibrium, if the conditions for the following three types of equilibrium are satisfied:

- (a) Mechanical equilibrium
- (b) Chemical equilibrium
- (c) Thermal equilibrium

(a) Mechanical equilibrium :

In the absence of any unbalanced force within the system itself and also between the system and the surrounding, the system is said to be in a state of mechanical equilibrium.

(b) Chemical equilibrium :

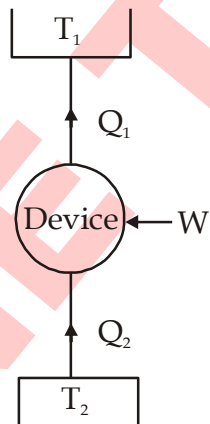
If there is no chemical reaction or transfer of matter from one part of the system to another, such as diffusion or solution, the system is said to exist in a state of chemical equilibrium.

(c) Thermal equilibrium :

When a system existing in mechanical and chemical equilibrium is separated from its surrounding by a diathermic change in any property of the system, the system is said to exist in a state of thermal equilibrium or equality of temperature.

(ii) Difference between heat pump and refrigeration cycle:

A refrigerator is a device which, operating in a cycle, maintains a body at a temperature lower than the temperature of surroundings. Performance parameter in a refrigerator cycle called the coefficient of performance, abbreviated to COP, which is defined as



$$\text{COP} = \frac{\text{Desired effect}}{\text{Work input}} = \frac{Q_2}{W}$$

$$\therefore [\text{COP}]_{\text{ref.}} = \frac{Q_2}{Q_1 - Q_2} \quad \dots(i)$$

A heat pump is a device which, operating in a cycle, maintains a body, at a temperature higher than the temperature of the surroundings. By virtue of the temperature difference, there will be heat leakage Q_1 from the body to the surroundings. The body will be maintained at the constant temperature t_1 , if heat is discharged into the body at the same rate at which heat leaks out of the body.

The COP is defined as

$$\text{COP} = \frac{Q_1}{W}$$

$$\therefore [\text{COP}]_{\text{H.P.}} = \frac{Q_1}{Q_1 - Q_2} \quad \dots(ii)$$

Relation between COP_{hp} and COP_R

We know that

$$COP_{REF} = \frac{Q_2}{Q_1 - Q_2}$$

Add one both side

$$COP_{REF} + 1 = \frac{Q_2}{Q_1 - Q_2} + 1$$

$$COP_{REF} + 1 = \frac{Q_1}{Q_1 - Q_2}$$

$$COP_{REF} + 1 = COP_{HP}$$

The Cop of heat pump is greater than the COP is a refrigerator by unity.

103.

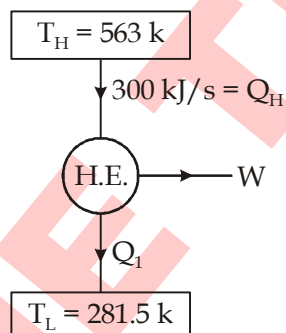
Sol. Given that

$$T_H = 563 \text{ k}$$

$$T_L = 281.5 \text{ k}$$

$$\eta_{rev} = 1 - \frac{T_L}{T_H} = 0.5$$

$$\eta_{rev} = 50\%$$



(i) If 125 kJ/s heat are rejected

i.e.

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

$$Q_H = 300 \text{ kJ/s}$$

$$\eta_1 = 1 - \frac{Q_L}{Q_H}$$

$$\eta_1 = 0.2833$$

$$\eta_1 = 28.33\%$$

$\eta_1 < \eta_{rev}$ This is a irreversible engine/cycle

(ii) If 150 kJ/s heat are rejected

$$\eta_2 = 1 - \frac{Q_L}{Q_H} = 1 - \frac{150}{300}$$

$$\eta_2 = 50\%$$

$\eta_2 = \eta_{rev}$ This is a reversible engine/cycle

(iii) If 75 kJ/s heat are rejected

$$\eta_3 = 1 - \frac{75}{300}$$

$$\eta_3 = 75\%$$

$\eta_3 > \eta_{rev}$ This is a impossible cycle/engine.

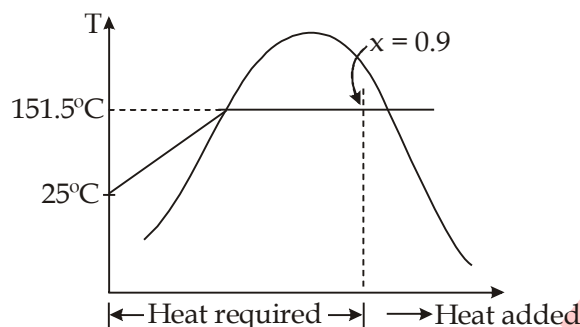
104.

Sol. Given that, Mass of water (m_P) = 2 kg

Initial temperature of water (T_1) = 25°C



Pressure of steam (P) = 5 bar
 Dryness Fraction of Steam (x) = 0.9
 Heat required to convert water into steam = ?



Heat required = Sensible Heat addition + Latent + Heat addition

Sensible heat addition = $mc_{pw}(t_s - t_1)$

where, t_s = Saturation temperature = 151.5°C at 5 bar [From steam table]

c_{pw} = Specific heat of water at constant pressure = 4.186 kJ/kg

$$\therefore \text{Sensible Heat addition} = 2 \times 4.186 \times (151.5 - 25) = 1059.058 \text{ kJ}$$

$$\Rightarrow \text{Latent heat addition/kg} = h \cdot h_{fg}$$

$$\Rightarrow \text{Latent heat } (h_{fg}) = 2107.4 \text{ kJ/kg From steam table at 5 bar}$$

$$\Rightarrow \text{Latent heat addition from 'm' kg} = m = m_f \cdot x \cdot h_{fg} = 2 \times 0.9 \times (2107.4) = 3793.32 \text{ kJ}$$

$$\text{Total heat required} = 1059.058 + 3793.32 = 4852.372 \text{ kJ}$$

105.

Sol. (i) From the definition of entropy,

$$dQ = Tds$$

From the first law of thermodynamics,

$$dW = PdV$$

Therefore,

$$TdS = dU + PdV$$

Or,

$$Tds = du + PdV$$

This is known as the first Tds or, **Gibbs equation**.

The second Tds equation is obtained by eliminating du from the above equation using the definition of enthalpy.

$$h = u + Pv$$

$$dh = du + v dP$$

Therefore,

$$Tds = dh - v dP$$

The two equations can be rearranged as

$$ds = (du/T) + (PdV/T)$$

$$ds = (dh/T) - (v dP/T)$$

Change of state for an ideal gas

If an ideal gas undergoes a change from P_1, v_1, T_1 to P_2, v_2, T_2 the change in entropy can be calculated by devising a reversible path connecting the two given states.

Let us consider two paths by which a gas can be taken from the initial state, 1 to the final state, 2. The gas in state 1 is heated at constant pressure till the temperature T_2 is attained and then it is brought reversibly and isothermally to the final pressure P_2 .

Path 1-a: reversible, constant-pressure process.

Path a-2: reversible, isothermal path

$$\Delta S_{1-a} = \int \frac{dq}{T} = \int C_p \frac{dT}{T} = C_p \ln \left(\frac{T_2}{T_1} \right)$$

$$\Delta S_{a-2} = \int \frac{dq}{T} = \int \frac{(du + pdv)}{T} = \int \frac{(pdv)}{T} = R \ln \left(\frac{v_2}{v_a} \right)$$

(Since $du = 0$ for an isothermal process)

Since

$$P_2 v_2 = P_a v_a = P_1 v_a$$

Or,

$$\frac{v_2}{v_a} = \frac{P_1}{P_2}$$

Or,

$$\Delta S_{a-2} = -R \ln \left(\frac{P_2}{P_1} \right)$$

Therefore,

$$\begin{aligned} \Delta S &= \Delta S_{1-a} + \Delta S_{a-2} \\ &= C_p \ln \left(\frac{T_2}{T_1} \right) - R \ln \left(\frac{P_2}{P_1} \right) \end{aligned}$$

Path 1-b-2: The gas initially in state 1 is heated at constant volume to the final temperature T_2 and then it is reversibly and isothermally changed to the final pressure P_2 .

1-b: reversible, constant volume process

b-2: reversible, isothermal process

$$\Delta S_{1-b} = C_v \ln \left(\frac{T_2}{T_1} \right)$$

$$\Delta S_{b-2} = R \ln \left(\frac{v_2}{v_1} \right)$$

or,

$$\Delta S = C_v \ln \left(\frac{T_2}{T_1} \right) + R \ln \left(\frac{v_2}{v_1} \right)$$

(ii) Difference between SI Engine and CI Engine:-

1. The compression ratio for a petrol engine is less. Hence the temperature after compression is much below the self ignition temperature of the fuel. Thus, a spark plug provided for combustion of the fuel in petrol engines.
In diesel engines, the compression ratio is very high. Hence the temperature of air after compression is above the self ignition temperature of the fuel. Due to this reason a spark plug is not necessary for diesel engine.
2. In petrol engines, the air and fuel get mixed in a carburettor before entering the engine cylinder. In diesel engines no mixing takes place between air and fuel before the start of suction stroke. Thus diesel engines do not have a carburettor.
3. For separate entry of fuel at the end of compression stroke, a nozzle (also known as injector) is provided for diesel engines. Petrol engines do not have a nozzle.
4. Heat addition takes place at constant pressure for diesel engines. It takes place at constant volume for petrol engines.
5. For the same compression ratio the efficiency of a petrol engine is higher than that of a diesel engine. But this is theoretical.
6. In actual practice the compression ratio of diesel engine is 1.5 times to 3 times more than that of petrol engine. Hence the efficiency of a diesel engine only is higher than the petrol engine.
7. For a diesel engine $\rightarrow r=16$ to 20
For petrol engine $\rightarrow r=6$ to 10
8. Under cruising condition/speed (Normal speed) the AF ratio for petrol engines is 16 and for diesel engine between 25 to 35.



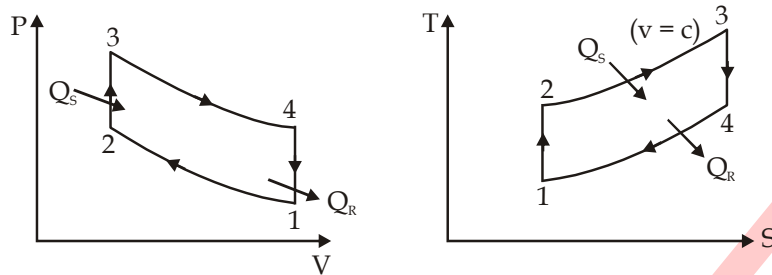
106.

Sol. Air Standard Cycles :-**Assumptions :-**

- (1) The working fluid is air and it is treated as an ideal gas.
- (2) Specific heat C_p & C_v are assumed to be constant.
- (3) The working fluid is of fixed mass. Closed system analysis
- (4) The working fluid does not undergo any chemical reaction i.e
- (5) All processes are assumed to be reversible (internally reversible)

Note :- Generally C_p & C_v of air are taken at 25°C . This analysis is known as cold air cycle analysis

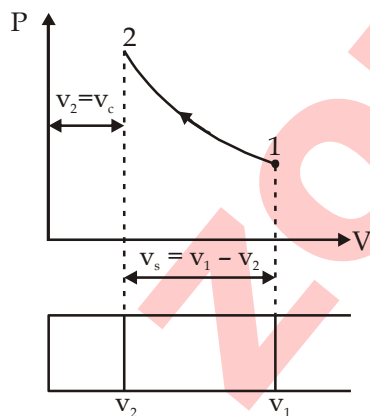
Otto Cycle



- 1 - 2 = Rev. adiabatic compression
- 2 - 3 = Constant volume heat addition
- 3 - 4 = rev. adiabatic expansion
- 4 - 1 = constant volume heat rejection

$$r = \frac{v_1}{v_2}$$

$$\eta = \frac{W_{\text{net}}}{Q_s} \Rightarrow \eta = 1 - \frac{Q_R}{Q_s}$$



2 - 3 process ($v = c$)

$$\delta Q = dU$$

$$\Rightarrow Q_s = mc_v (T_3 - T_2)$$

4 - 1 process ($v = c$)

$$Q_R = mc_v (T_1 - T_4)$$

$$-Q_R = mc_v (T_4 - T_1) \text{ heat rejection}$$

$$\eta = 1 - \frac{mc_v(T_4 - T_1)}{mc_v(T_3 - T_2)} \Rightarrow \eta = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)}$$

$$\eta = 1 - \frac{T_1 \left(\frac{T_4}{T_1} - 1 \right)}{T_2 \left(\frac{T_3}{T_2} - 1 \right)}$$

1 - 2 (rev. adiabatic)

$$T_1 V_1^{r-1} = T_2 V_2^{r-1}$$

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2} \right)^{r-1} = (r)^{r-1} \dots (i)$$

3 - 4 (rev adiabatic expansion)

$$T_3 V_3^{r-1} = T_4 V_4^{r-1} \quad v_4 = v_1 \quad v_3 = v_2$$

$$\frac{T_3}{T_4} = \left(\frac{V_4}{V_3} \right)^{r-1} \Rightarrow \left(\frac{V_1}{V_2} \right)^{r-1}$$

$$\frac{T_3}{T_4} = (r)^{r-1} \dots (ii)$$

from (i) and (ii)

$$\frac{T_2}{T_1} = \frac{T_3}{T_4}$$

$$T_1 T_3 = T_2 T_4$$

$$\frac{T_4}{T_1} = \frac{T_3}{T_2} \Rightarrow \frac{T_4}{T_1} - 1 = \frac{T_3}{T_2} - 1$$

$$\eta = 1 - \frac{T_1 \left(\frac{T_4}{T_1} - 1 \right)}{T_2 \left(\frac{T_3}{T_2} - 1 \right)}$$

$$\Rightarrow \eta = 1 - \frac{T_1}{T_2}$$

$$\eta = 1 - \frac{1}{(r)^{r-1}}$$

107.

Sol. The first law in differential form is given as

$$\delta Q = \delta U + \delta W$$

For a reversible process,

$$\delta W = PdV$$

$\therefore$

$$\delta Q = dU + PdV$$

as

$$\delta Q = 0 \text{ for an adiabatic process}$$

$\therefore$

$$dU + PdV = 0$$

...(i)

For an ideal gas

$$PV = RT \text{ or } P = \frac{RT}{V}$$

Substituting in equation (i),

$$dU + \frac{RT}{V} dV = 0$$

Also for an ideal gas,

$$U = c_v T \text{ or } dU = c_v dT$$

$\therefore$

$$c_v dT + \frac{RT}{V} dV = 0$$

Dividing by T,

$$\frac{c_v dT}{T} + \frac{R}{V} dV = 0$$

Integrating,

$$c_v \ln T + R \ln V = \text{constant}$$

Substituting, $T = \frac{PV}{R}$

$$c_v \ln \frac{PV}{R} + R \ln V = \text{constant}$$

$$\ln \frac{PV}{R} + \frac{R}{c_v} \ln V = \text{constant}$$

We know $c_v = \frac{R}{\gamma-1}$ or $\frac{R}{c_v} = \gamma - 1$

$$\therefore \ln \frac{PV}{R} + (\gamma - 1) \ln V = \text{constant}$$

$$\ln \frac{PV}{R} + \ln V^{\gamma-1} = \text{constant}$$

$$\ln \frac{PV^{1+\gamma-1}}{R} = \text{constant}$$

$$\ln \frac{PV^\gamma}{R} = \text{constant}$$

$$PV^\gamma = R \times e^{\text{constant}}$$

$$PV^\gamma = \text{Constant}$$

108.

Sol. When ever a closed system undergoes a cyclic process, the cyclic integral $\oint \frac{dQ}{T}$ is less than zero (i.e., negative) for an irreversible cyclic process and equal to zero for a reversible cyclic process. The efficiency of a reversible H.E. operating within the temperature T_1 and T_2 is given by :

$$\eta = \frac{(Q_1 - Q_2)}{Q_1} = \frac{(T_1 - T_2)}{T_1} = 1 - \left(\frac{T_2}{T_1} \right)$$

i.e., $1 - \frac{Q_2}{Q_1} = 1 - \frac{T_2}{T_1}$ or $\frac{Q_2}{Q_1} = \frac{T_2}{T_1}$ or $\frac{Q_1}{T_1} = \frac{Q_2}{T_2}$

or $\frac{Q_1}{T_1} - \left(-\frac{Q_2}{T_2} \right) = 0$

Since Q_2 is heat rejected so -ve

or $\oint \frac{dQ}{T} = 0$ for a reversible engine. ... (i)

Now the efficiency of an irreversible H.E. Operating within the same temperature limit T_1 and T_2 is given by

$$\eta = \frac{(Q_1 - Q_2)}{Q_1} < \frac{(T_1 - T_2)}{T_1}$$

i.e., $1 - \frac{Q_2}{Q_1} < 1 - \frac{T_2}{T_1}$

or
$$-\frac{Q_2}{Q_1} < \frac{T_2}{T_1} \text{ or } \frac{Q_1}{T_1} < \frac{Q_2}{T_2}$$

or
$$\frac{Q_1}{T_1} - \left(-\frac{Q_2}{T_2}\right) < 0$$

Since Q_2 is heat rejected so -ve

$$\frac{Q_1}{T_1} + \frac{Q_2}{T_2} < 0$$

or
$$\oint \frac{dQ}{T} < 0 \text{ for an irreversible engine.} \quad \dots(ii)$$

Combine equation (i) and (ii), we get

$$\oint \frac{dQ}{T} \leq 0$$

The equation for irreversible cyclic process may be written as :

$$\oint \frac{dQ}{T} + I = 0$$

I = Amount of irreversibility of a cyclic process.

109.

Sol. **Type of work:**

- (a) **Closed system work or Non-flow work:** To obtain the closed system work area under p-V curve should be projected on volume axis and mathematical expression of closed system work is,

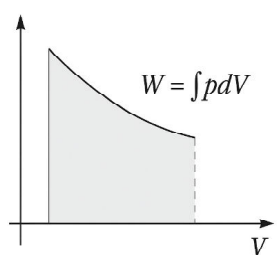
$$W = \int p dV$$

- (b) **Open system work or Steady work:** To obtain the open system work area under p-V curve should be projected on pressure axis. Mathematical expression of open system work is given as

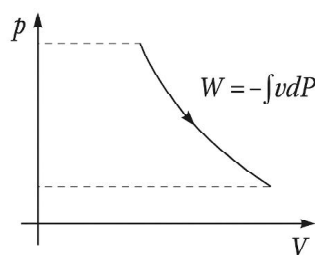
$$W = -\int V dp$$

Other types of work transfer:

1. Electrical work
2. Shaft work
3. Paddle-wheel work or stirring work



Closed system work



Open system work

4. Flow work
5. Work done in stretching a wire
6. Work done in changing the area of a surface film
7. Magnetization of a paramagnetic solid.

Flow work: It is the amount of work which is required to displace a infinitely small fluid element into or out from control volume. Flow work is a point function and it is expressed as

$$W_{\text{flow}} = pv \text{ (kJ/kg)}$$

It is interesting that unlike other work quantities, flow work is expressed in terms of properties. In fact, it is the product of two properties of the fluid. For that reason, it is viewed as a combination property (like enthalpy) and referred as flow energy, convected energy, or transport energy instead of flow work and that's why it is stated as a point function.

Steady flow energy equation: When the properties are not varying with respect to time then it is known as steady flow. The mass flow rate the entry and exit of control volume is always same.

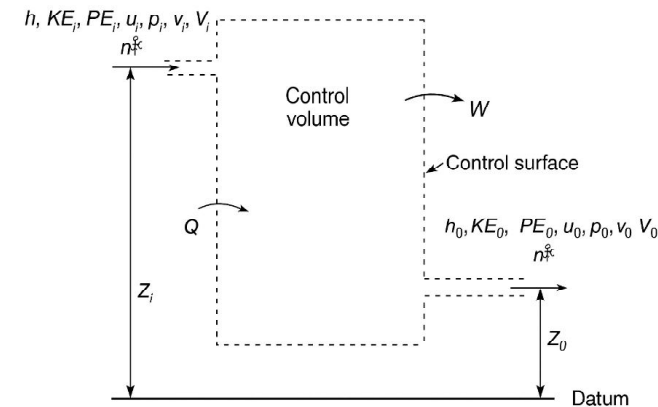
Let us assume,

h = Specific enthalpy, KE = Specific kinetic energy, PE = Specific potential energy,

u = Specific internal energy, pv = Flow work, V = Velocity, m = Mass flow rate, Z = Datum head

Q = Heat supplied, W = Work done by the system

Subscript 'i' and 'o' represents the inlet and outlet condition of control volume.



$$u_i + P_i V_i + KE_i + PE_i + Q = u_o + P_o V_o + KE_o + PE_o + W$$

$$h_i + \frac{V_i^2}{2000} + \frac{gZ_i}{1000} + Q = h_o + \frac{V_o^2}{2000} + \frac{gZ_o}{1000} + W$$

$$\dot{m} \left(h_i + \frac{V_i^2}{2000} + \frac{gZ_i}{1000} \right) + \dot{Q} = \dot{m} \left(h_o + \frac{V_o^2}{2000} + \frac{gZ_o}{1000} \right) + \dot{W}$$

- (i) **Throttling device:** Flow through a restricted passage, partially open valve, porous plug etc, is known as throttling. It is used for isenthalpic processor. Throttling always results in decrement of pressure and it is a irreversible adiabatic process.

Assumption:

- (a) Neglecting changes in KE and PE
 (b) It is an adiabatic process and there is no work interaction.
 By SFEE,

$$h_i + KE_i + PE_i + Q = h_o + KE_o + PE_o + W$$

After considering assumptions

$$h_i = h_o$$

- (ii) **Compressor:** It is work absorbing device, in which energy is transferred from rotor to working fluid. It is used for increasing both pressure and temperature of gaseous phase of working fluid.

Assumption:

- (a) Neglecting changes in KE and PE
 (b) Assuming it to be well insulated, $Q = 0$
 By SFEE,

$$h_i + KE_i + PE_i + Q = h_o + KE_o + PE_o + W$$

After considering assumption,

$$h_i = h_o + W$$

$$W = (h_i - h_o)$$

- $\therefore$ Compressor is work absorbing device,

$$\text{Work required} = (h_o - h_i)$$

110.

Sol.

(i) If

$$u = f(T, v)$$

$$du = \left(\frac{\partial u}{\partial T} \right)_v dT + \left(\frac{\partial u}{\partial v} \right)_T dv \quad \dots(i)$$

Now the first Tds equation is

$$Tds = c_v dT + T \left(\frac{\partial p}{\partial T} \right)_v dv \quad \dots(ii)$$

From first law of thermodynamics

$$du = Tds - pdv \quad \dots(iii)$$

From Eqs. (ii) and (iii)

$$du = c_v dT + T \left(\frac{\partial p}{\partial T} \right)_v dv - pdv = c_v dT + \left[T \left(\frac{\partial p}{\partial T} \right)_v - p \right] dv \quad \dots(iv)$$

Now as

$$\beta = \frac{1}{v} \left(\frac{\partial v}{\partial T} \right)_p : k = - \frac{1}{v} \left(\frac{\partial v}{\partial p} \right)_T$$

$$\frac{\beta}{k} = - \left(\frac{\partial v}{\partial T} \right)_p \left(\frac{\partial p}{\partial v} \right)_T$$

Now

$$\left(\frac{\partial v}{\partial T} \right)_p \left(\frac{\partial T}{\partial p} \right)_v \left(\frac{\partial p}{\partial v} \right)_T = -1$$

or

$$\left(\frac{\partial v}{\partial T} \right)_p \left(\frac{\partial p}{\partial v} \right)_T = - \left(\frac{\partial p}{\partial T} \right)_v$$

∴

$$\frac{\beta}{k} = \left(\frac{\partial p}{\partial T} \right)_v$$

Substituting this in Eq. (iv), we get

$$du = c_v dT + \left[T \frac{\beta}{k} - p \right] dv$$

(ii) Now we know that

$$dh = Tds + vdp$$

...(v)

Writing second Tds equation: $Tds = c_v dT - T \left(\frac{\partial v}{\partial T} \right)_p dp$

...(vi)

$$\therefore dh = c_v dT - T \left(\frac{\partial v}{\partial T} \right)_p dp + vdp = c_p dT + \left[-T \left(\frac{\partial v}{\partial T} \right)_p + v \right] dp$$

We know

$$\beta = \frac{1}{V} \left(\frac{\partial v}{\partial T} \right)_p$$

$$\therefore dh = c_p dT + [1 - \beta T] v dp$$

111.

Sol. Diesel cycle

$$\eta = 1 - \frac{1}{(r_c)^{\gamma-1}} \frac{[\rho^\gamma - 1]}{[\gamma(\rho - 1)]}$$

Where

$$r_c = \text{Compression ratio} = \frac{V_1}{V_2}$$

$$\rho = \text{Cut-off ratio} = \frac{V_3}{V_2}$$

$$\gamma = \frac{C_p}{C_v}$$

Given :

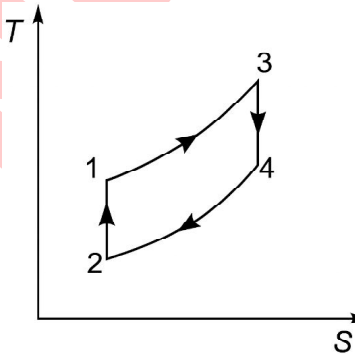
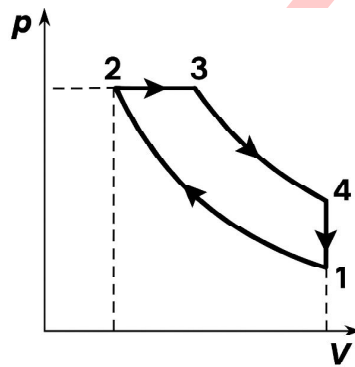
$$C_v = 0.717 \text{ kJ / kgK}$$

$$\gamma = 1.4$$

$$C_p = 1.0038 \text{ kJ / kgK}$$

$$\therefore R = C_p - C_v = 0.2868 \text{ kJ / kgK}$$

$$\therefore (\eta)_{\text{Diesel}} = 1 - \frac{1}{(16)^{0.4}} \frac{[\rho^{1.4} - 1]}{1.4(\rho - 1)}$$



Where

$$\rho = \text{Cut off ratio} = \frac{V_3}{V_2}$$

$$V_3 - V_2 = 0.10(V_1 - V_2)$$

$$\left(\frac{V_2}{V_3} - 1\right) = 0.10 \left(\frac{V_1}{V_2} - 1\right)$$

$$(\rho - 1) = 0.10(16 - 1)$$

$$\rho = 2.5$$

$$\therefore (\eta)_{\text{Diesel}} = 1 - \frac{1}{(16)^{0.4}} \left[\frac{(2.5)^{1.4} - 1}{1.4(2.5 - 1)} \right] = 0.5905$$



Case -II

When C_v is decreases by 2% $C'_v = 0.98 \times C_v$

i.e. $C'_v = 0.70566 \text{ kJ / kgK}$

$$R = 0.2868 = C'_p - C'_v$$

$$C'_p = 0.98946 \text{ kJ / kgK}$$

$$\therefore \gamma' = \frac{C'_p}{C'_v} = 1.4081$$

$$\therefore (\eta_{||})_{\text{Diesel}} = 1 - \frac{1}{(16)^{0.4081}} \frac{[(2.5)^{1.4081} - 1]}{[(1.4081)(2.5 - 1)]} = 0.5978$$

$$\therefore \% \text{ increase in efficiency of diesel cycle} = \frac{0.5978 - 0.5905}{0.5905} = 1.236\%$$

