THERMODYNAMICS

(CBCGS DEC 2018)

1. Solve the following (any Four)

(a) State first law of thermodynamics for closed system. State its limitations. (5)

SOLUTION:

The first law of thermodynamics is a version of the law of conservation of energy, The law of conservation of energy states that the total energy of an isolated system is constant; energy can be transformed from one form to another, but can be neither created nor destroyed. The first law is often formulated.

$$\Delta U = Q - W$$

It states that the change in the internal energy ΔU of a closed system is equal to the amount of heat Q supplied to the system, minus the amount of work W done by the system on its surroundings. An equivalent statement is that perpetual motion machines of the first kind are impossible.

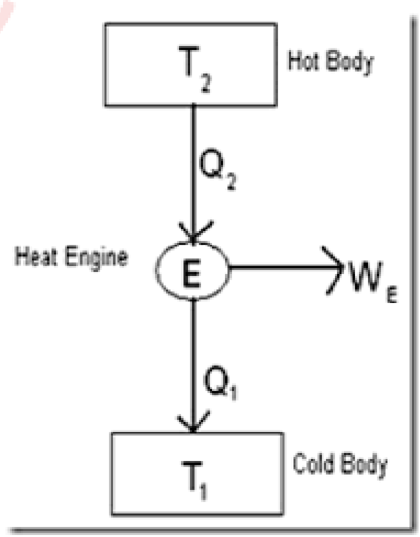
The limitations of first law -

- It does not tells us about direction in which heat flows when they are in contact
- It does not tell about the final temperature of two bodies when they are in direct contact.
- It does not tell about the entropy of system.

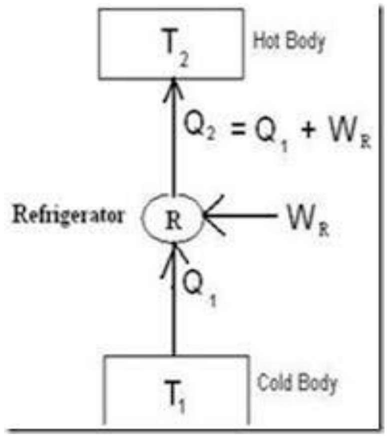
(b) Explain heat engine, heat pump and refrigerator with the help of neat sketch. (5)

SOLUTION:

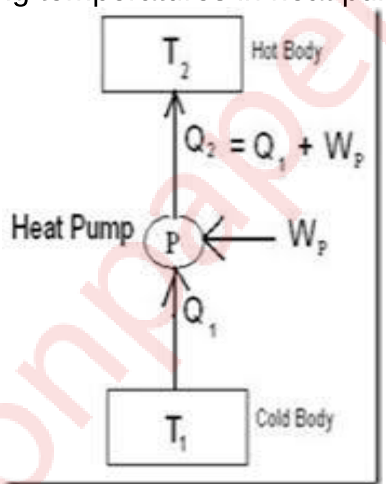
1. In a heat engine, heat is transferred from a higher temperature level called source to a lower temperature level called sink. Work is obtained during this process.



2. A refrigerator is a reversed heat engine. Heat is transferred from the lower temperature level to higher temperature by applying external work to maintain the temperature below atmospheric temperature.



3. A heat pump is similar to a refrigerator. The only point of difference between the two is of the operating temperatures. The working temperatures in a refrigerator are of the colder level and atmosphere, whereas working temperatures in heat pump are of hotter level and



atmosphere.

(c) Explain free air delivered and volumetric efficiency. Write their equations also. (5)

SOLUTION:

FAD (Free Air Delivery) is the actual quantity of compressed air converted back to the inlet conditions of the compressor. The units for FAD are CFM in the imperial system and l/min in the SI system. The units are in general measured according the ambient inlet standard conditions ISO.

$$\mathrm{FAD} = \frac{P_a V_a T_o}{P_o T_a}$$

where-
Pa, Ta, Va are at atmospheric condition and To, Po at NTP i.e. To=293K and Po=1 bar.

Volumetric efficiency is defined as the ratio of gas volume taken during suction to the swept volume.

$$\eta_v = 1 - \left[(r_p)^{1/n} - 1\right]C$$

(d) Define: available energy, dead state and irreversibility. (5)

SOLUTION:

Available energy: Availability or Energy is the maximum portion of energy that can be converted into work by ideal process that reduces the system to dead state.

Dead state: Any system that has temperature T and pressure P can do useful work till the temperature and pressure are reduced to T_0 and P_0. When the temperature and pressure are equal to that of the earth or dead state all transfer of energy, stops although the system contains internal energy which would be unavailable.

Irreversibility: The actual work done by a system is always less than idealized reversible work and the difference between the two is called the irreversibility of the process

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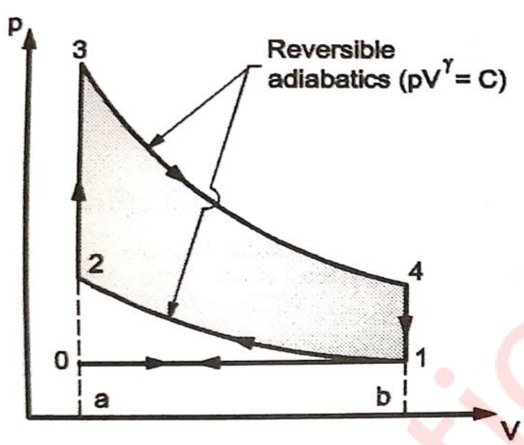
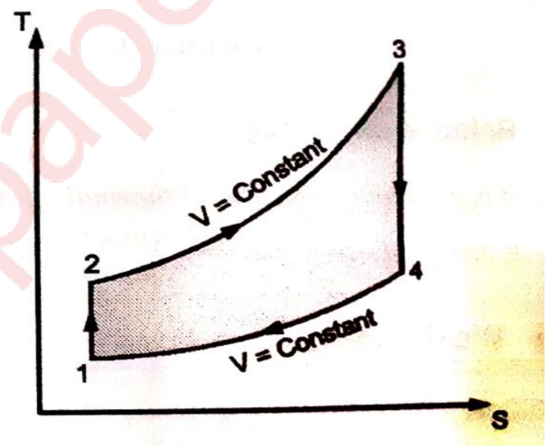
(e) Explain working of Otto cycle with the help of PV and TS diagram. Write the equation for efficiency of the cycle. (5)

Solution:





Otto cycle consists of two constant volumes and two reversible adiabatic processes. Consider m kg of air in the cycle at state 1.

The various processes are:

Process 1-2: Reversible adiabatic compression or isentropic compression during which air is compressed from state 1 to state 2. The law of process is $pV^{\gamma} = C$

Process 2-3: Heat is added to air from a heat reservoir at constant volume and state changes from state 2 to state 3. Heat supplied, $Q_{2-3} = mC_v(T_3 - T_2)$.

Process 3-4: The air expands from state 3 to state 4 reversible adiabatically according to law $PV^{\gamma} = C$.

Process 4-1: During this process heat is rejected at constant volume and the system returns to its original state. Therefore, a cycle is completed. Heat rejected, $Q_{4-1} = mC_v(T_4 - T_1)$.

Thermal efficiency (air-standard efficiency) of Otto Cycle,

$$\eta_{th} = \frac{\text{Heat Supplied - Heat Rejected}}{\text{Heat Supplied}}$$

$$\eta_{th} = \frac{mC_v\left(T_3 - T_2\right) - mC_v\left(T_4 - T_1\right)}{mC_v\left(T_3 - T_2\right)}$$

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

(f) Define types of steam and represent it on p-v diagram for water. (5)

SOLUTION:

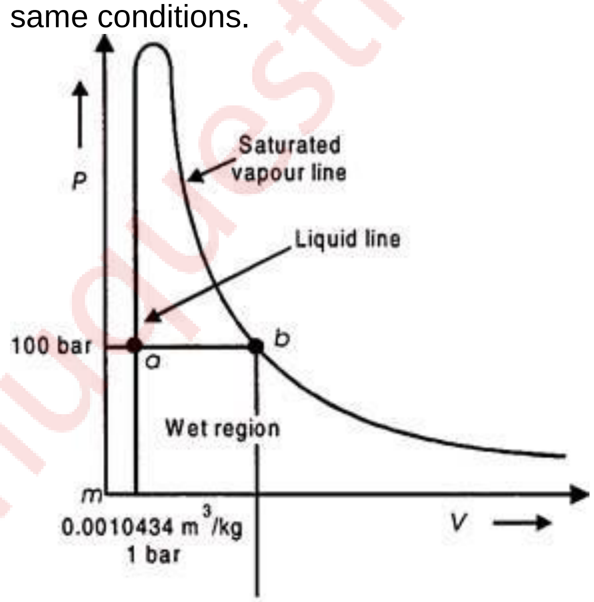
Steam exists in following types:

i) Wet steam (saturated steam): If saturated steam contains liquid particles, it is known as wet steam. It does not contain sufficient heat energy to maintain all water in a gaseous state.

ii) Dry steam (dry saturated steam): If saturated steam does not contain any water, it is known as dry and saturated steam. It contains just sufficient heat energy to maintain all the water in a gaseous state.

iii) Superheated steam: If the temperature of the steam is greater than that of the boiling point or saturation temperature corresponding to the pressure of steam generation, the steam is known as superheated steam.

iv) Supersaturated steam: Supersaturated steam at a particular saturation pressure has temperature less and density greater than the corresponding values given in the steam tables. This condition of steam is obtained when it is cooled by its own expansion until it contains less heat energy than the saturated steam under the same conditions.



Q2.

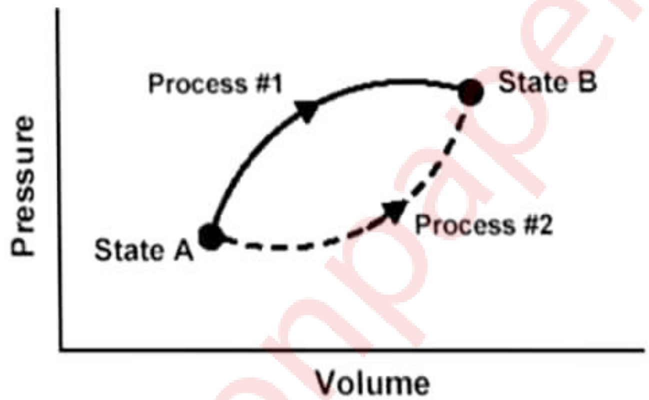
(a) **3 kg of air at a pressure of 150 kPa and temperature 360 K is compressed 12 polytropically to 750 kPa according to law $PV^{1.25}$=C. The gas is.then cooled to initial temperature at constant pressure. The air is then expanded at constant temperature till it reaches original pressure of 150 kPa. Draw the cycle on p-V diagram and determine net work and heat transfer.** **(12)**

SOLUTION:

(b) **Prove that energy is property of the system.** **(8)**

SOLUTION:

Let us assume that we have one system which is undergoing a change of state from initial state 1 to another state 2 via following the path A as shown in following figure. System is returning to initial state i.e. state 1 from state 2 via following the path B. Here, we can say that system is undergoing in a cycle 1-2-1 as displayed in figure.



From the first law of thermodynamics for a system undergoing a change of state and apply for path A, where system is changing its state from state 1 to state 2. We will have following equation

$$Q_A - W_A = \Delta E_A$$

Similarly, we will have following equation when system is changing its state from state 2 to state 1 via following the path B.

$$Q_B - W_B = \Delta E_B$$

We have already seen that system is undergoing in a cycle 1-2-1 as displayed in above figure. The equation for system which constitutes a cycle 1-2-1 and we will have following equation.

$$\sum_{Cycle} W = \sum_{cycle} Q$$

$$W_A + W_B = Q_A + Q_B$$

$$W_B - Q_B = Q_A - W_A$$

$$-(Q_B - W_B) = Q_A - W_A$$

$$-(\Delta E_B) = \Delta E_A$$

Let us assume that system is returning to initial state 1 from state 2 via following the path C, in that case we will go ahead similarly as we have gone above and finally we will have following equation

$$-(\Delta E_C) = \Delta E_A$$

Now if we will look the end result for first case where system is returning to initial state by following the path B and of second case where system is returning to initial state by following the path C, what we will secure here that change in system energy is same in both cases and it will not depend over the path followed by the system to return to its initial state.

Therefore we can conclude that system energy will have some definite magnitude for each state of the system and it will not depend over the path followed by the system and hence energy will be considered as a point function and also a property of the system.

Q3.

(a) In a steady flow device, the inlet and outlet. Conditions are given below. Determine the heat loss or gain by the system in kW. Fluid flow rate through the device is 2.1 kg/s and work output of the device is 750 kW. (8)

Property	**Inlet**	**Outlet**
Pressure (bar)	**10**	**8.93**
Specific enthalpy (kJ/kg)	**2827**	**2341**
Velocity (m/s)	**20**	**120**
Elevation (m)	**3.2**	**0.5**

SOLUTION:

m= 2.1kg/s

W=750kW

C1= 20 m/s

C2= 120 m/s

Z_2=0.5 m

Z_1= 3.2 m

Applying the steady flow energy equation at inlet and outlet:

$$Q - W = m[(h_2 - h_1) + \frac{(C_2^2 - C_1^2)}{2} + (Z_2 - Z_1)g$$

$$Q - 750 = 2.1[(2341 - 2827) + \frac{120^2 - 20^2}{2} + (0.5 - 3.2)9.81]$$

Q = 12.873 kJ.

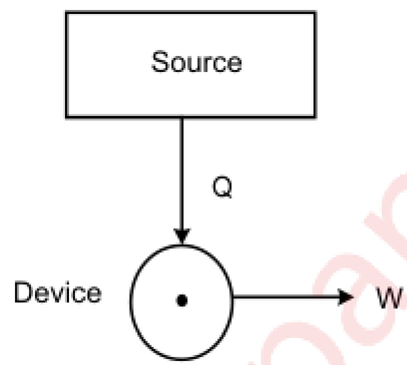
As the answer is positive, heat is transferred to the system.

(b) Explain Kelvin-Planck & Clausius statement with the help of sketch. (6)

SOLUTION:

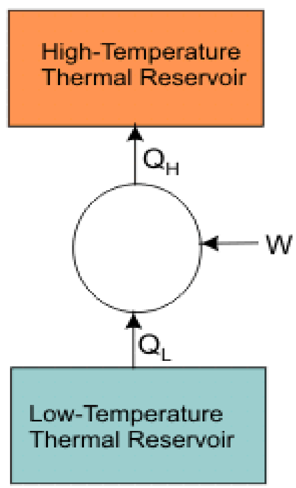
Kelvin–Planck statement:
Kelvin – Planck statement states "it is impossible to construct an engine, which is operating in a cycle produces no other effect except to external heat from a single reservoir and do equivalent amount of work.

It considers the transformation of heat into work. the concept of perpetual motion machine of the second kind (PMMSK or PMM2), that is, of a device which would perform work solely by absorbing energy as heat from a body. Such a device does not violate the first law of thermodynamics.



A PMMSK is a hypothetical device which working cyclically, receives energy as heat from a single thermal reservoir, and delivers as equivalent amount of work. The Kelvin-Planck statement of the second law tells us that it is impossible to constructs a perpetual motion machine of the second kind.

Clausius statement:
Clausius statement states "it is impossible for a self-acting machine working in a cyclic process without any external force, to transfer heat from a body at a lower temperature to a body at a higher temperature. It considers transformation of heat between two heat reservoirs. Consider the case of a refrigerator or a heat pump.



When $W = 0,$

$(COP)_R \to \infty$ and $(COP)_{HP} \to \infty$

It is impossible to construct a refrigerator or a heat pump whose COP is infinity. Consider a domestic refrigerator, this device extracts energy as heat from the substance to be coded and transfers it to the surroundings. The refrigerator is supplied with electric power. Energy transfer as heat from a high temperature body to a low temperature body is a spontaneous process. The Clausius statement of the second law of thermodynamics tells that this spontaneous process cannot proceed in the reverse direction.

(c) A heat engine receives 1000 kW of heat at constant temp of 285°C. The heat is rejected at 5 °C. The possible heats rejected are: 840kW, 492kW and 300 kW. Classify the cycle into reversible, irreversible and impossible using Clausius Inequality theorem.

(6)

SOLUTION:

Q_1= 1000 kW

T_1= 285°C=558 K

T_2= 5°C = 278 K

According to Clausius inequality,

$$\sum \frac{Q}{T} \leq 0$$

Cycle's sign of equality holds good for reversible cycles and inequality for irreversible cycles.

Case 1: When $Q_2 = 850\text{kW}$

For cycle; $\sum \frac{Q}{T} = \frac{Q_1}{T_1} + \frac{Q_2}{T_2} = \frac{1000}{558} + \frac{-840}{278} = -1.2295 \text{ kW/K}$

As the value is less than zero, the cycle is irreversible.

Case 2: When $Q_2 = 492 \text{ kW}$

For cycle; $\sum \frac{Q}{T} = \frac{1000}{558} - \frac{492}{278} = 0.000748 \text{ kW/K}$

As the value is approximately equal to zero, the cycle is reversible.

Case 3: When $Q_2 = 300\text{kW}$

For cycle; $\sum \frac{Q}{T} = \frac{1000}{558} - \frac{300}{278} = 0.713 \text{ kW/K}$

As the value is more than than zero, the cycle is impossible.

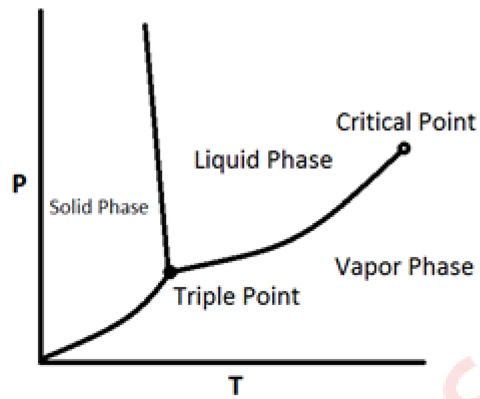
Q4.

(a) Define Critical Point and Triple point. Draw p-T diagram for water and show these points on it. **(6)**

SOLUTION:

A critical point (or critical state) is the end point of phase equilibrium. The point at which saturated liquid and saturated vapour lines meet is called the critical point. At critical point there is no distinction between the liquid and vapour phases, below critical point the substances exists in a two phases. An example is example is the liquid-vapor critical point, the end point of the pressure-temperature curve that designates conditions under which a liquid and its vapor can coexist.

Triple point of a substance is the temperature and pressure at which the three phases (gas, liquid, and solid) of that substance coexist in thermodynamic equilibrium. The point at which fusion line and sublimation line and vaporization meet is called the triple point. At triple point all the three phases can coexist together in equilibrium. The triple point of water is defined to take place at 273.16 K, where K is the SI unit Kelvin.



(b) Write four Maxwell relations. **(4)**

SOLUTION:

$$dU = TdS - PdV \quad \Longrightarrow \left(\frac{\partial T}{\partial V}\right)_S = -\left(\frac{\partial P}{\partial S}\right)_V$$

$$dA = -SdT - PdV \quad \Longrightarrow \left(\frac{\partial S}{\partial V}\right)_T = \left(\frac{\partial P}{\partial T}\right)_V$$

$$dH = TdS + VdP \quad \Longrightarrow \left(\frac{\partial T}{\partial P}\right)_S = \left(\frac{\partial V}{\partial S}\right)_P$$

$$dG = -SdT + VdP \quad \Longrightarrow -\left(\frac{\partial S}{\partial P}\right)_T = \left(\frac{\partial V}{\partial T}\right)_P$$

(c) A house is. maintained at a temperature of 20°C by means of a heat pump in winter by pumping heat from the atmosphere. Heat losses through the walls of the house are estimated at 0.65 kJ/K temperature different between inside of the house and outside atmosphere.

(i)If atmospheric temperature is —10°C, what is minimum amount of power required to drive the heat pump?

(ii)It is proposed to use the same heat pump to cool the house in summer. If the same amount of power is supplied to heat pump then what is the maximum permissible atmospheric temperature? **(10)**

SOLUTION:

Q5.

(a) Draw Carnot cycle, Stirling cycle and Ericsson cycle on common T-S diagram. Mention all the process on the diagram. (6)

SOLUTION:

(b) Write the classifications of air compressors. (4)

SOLUTION:

An air compressor is a device that converts power into potential energy stored in pressurized air.

Compressors can be classified according to the pressure delivered:

1. Low-pressure air compressors (LPACs), which have a discharge pressure of 150 psi or less
2. Medium-pressure compressors which have a discharge pressure of 151 psi to 1,000 psi
3. High-pressure air compressors (HPACs), which have a discharge pressure above 1,000 psi[2]

They can also be classified according to the design and principle of operation:

1. Single-Stage Reciprocating Compressor
2. Two-Stage Reciprocating Compressor
3. Compound Compressor
4. Rotary-screw compressor
5. Rotary Vane Compressor
6. Scroll Compressor
7. Turbo compressor
8. Centrifugal compressor

(c) A single stage, single acting reciprocating air compressor delivers 0.6 kg/min of air at 6 bar. The temperature and pressure at the suction stroke are 30°C and 1 bar respectively. The bore and stroke are 100 mm and 150 mm respectively. The clearance volume is 3% of the swept volume and index of expansion and compression is 1.3.

Determine (i) Volumetric efficiency of compressor (ii) Indicated power (iii) Speed of the compressor in rpm. (10)

SOLUTION:

Given: m=0.6 kg/min

$P_2 = 6 \text{ bar} = 600\text{kPa}$

$T_1 = 30°C = 303K$

$P_1 = 1 \text{ bar} = 100\text{kPa}$

Bore; d=100 mm= 0.1m L=150mm = 0.15m

C=3%=0.03

Index, n=1.3

Mechanical efficiency, $\eta_m = 0.85$

Volumetric efficiency;

$$\eta_v = 1 - C\left[\left(\frac{P_2}{P_1}\right)^{1/n} - 1\right] = 1 - 0.03\left[\left(\frac{6}{1}\right)^{1/1.3} - 1\right]$$

=0.911 or 91.1%

Power required to drive the compressor if $\eta_m = 0.85$

$$I.P. = \left(\frac{n}{n-1}\right) mRT_1 \left[\left(\frac{P_2}{P_1}\right)^{n-1/n} - 1\right]$$

$$= \left(\frac{1.3}{0.3}\right) X \frac{0.6}{60} X\ 0.287\ X\ 303\ [(6)^{0.3/1.3} - 1]$$

= 1.9297 kW

$$B.P. = \frac{I.P.}{\eta_m} = \frac{1.9297}{0.85} = 2.27\ kW$$

Speed of compressor;

$$\mathbf{P_1(V_1 - V_4) = mRT_1}$$

$$\mathbf{100(V_1 - V_4) = 0.6X0.287X303}$$

$\mathbf{(V_1 - V_4)}$= 0.5218 $\mathbf{m^3/min}$

Rate of stroke volume,

$$\dot{V}_s = \frac{(V_1 - V_4)}{\eta_v} = \frac{0.5218}{0.919} = 0.5678\ m^3/min$$

But $\dot{V}_s = V_s X N = \frac{\pi}{4} d^2 L\ N$

0.5678 = $\frac{\pi}{4}(0.1^2)X0.15XN$

N= 481.96 rpm

Q6)

(a)A steam power plant has boiler and condenser pressure of 60 bar and 0.1 bar respectively. Steam coming out of the boiler is dry and saturated. The plant operates on Rankine cycle. Calculate the thermal efficiency of the cycle. (5)

SOLUTION:

(b)Explain the working of vane type rotary air compressor with the help of sketch. (5)

SOLUTION:

Rotary Vane Air Compressors use a centrifugal motion to generate compressed air rather than the reciprocating motion of the compressor piston pump. The Vane Compressors concept:

In an air tool, compressed air enters the inlet port which is plumbed to the smallest compartment of the vane-housing inside the air tool. Compressed air moves from an area of high pressure as it enters the air tool the air “wants’ to move to an area of relative low pressure, that being back to atmospheric pressure outside the air tool. As the air moves inside the tool from the high pressure area to the low, it too moves the vanes causing a centrifugal motion of those vanes and a rotary motion of the shaft to which the vanes are connected. It is the compressed air, moving from a high pressure area to a low pressure exhaust port in the air tool that rotates the vanes and drives the air tool.

Vane Operation

The vanes inside the vane compressor are installed in eccentrically located center housing. The vanes are able to slide in and out.

Though all the vanes may be the same length, their reach inside the vane housing depends on where they are in relation to the outer bare as the vane housing is off-center in relation to the outer barrel.

Centrifugal force or internal springs continuously press all the vanes against the inner-wall of the outer barrel as the housing rotates inside the compression chamber. This seals each vane against the outer surface, creating relatively air tight compartments within.

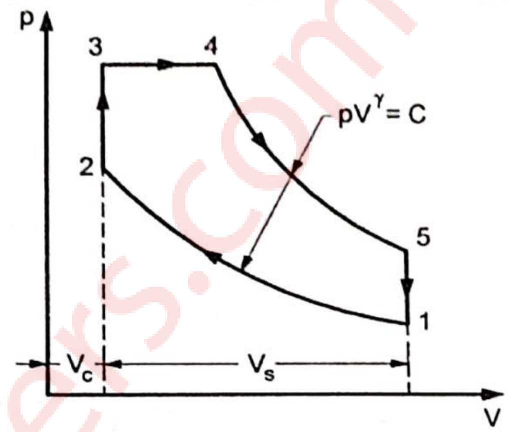
Where the volume between the vanes is largest, free air is drawn into the compressor vane-housing through an inlet valve.

As the center shaft continues to rotate, and since it is off-center to the cylinder, the succeeding compartments between the vanes are smaller and smaller, being closer to the outer wall.

The result is a larger volume of air is compressed into a smaller volume and the now-compressed air is released through another valve into a compressor tank or compressor receiver or into the shop air mains.

(c) In an air standard Dual cycle, pressure and temperature are 0.1 MPa and 27°C. Compression ratio is 18. The pressure ratio for constant volume part of heating process is 1.5 and volume ratio for the constant pressure part of heating is 1.2, Determine (i) Thermal efficiency (ii) Mean effective pressure in MPa. (10)

SOLUTION:



Given : $p_1 = 0.1 \text{ MPa} = 1 \text{ bar}, \; T_1 = 27°C = 300 \text{ K}$

Compression ratio, $r = \frac{V_1}{V_2} = 18$

Pressure ratio in constant volume heating process,

$$\frac{p_3}{p_2} = \alpha = 1.5$$

Volume ratio in constant pressure heating process,

$$\frac{V_4}{V_3} = \rho = 1.2$$

(i) Thermal efficiency, η

Consider isentropic process (1-2)

$$T_2 = T_1\left(\frac{V_1}{V_2}\right)^{(\gamma-1)} = 300\,(18)^{0.4} = 953.3 \text{ K}$$

$$p_1 V_1^\gamma = p_2 \cdot V_2^\gamma \; ; \qquad p_2 = p_1 \times \left(\frac{V_1}{V_2}\right)^\gamma = 1\,(18)^{1.4} = 57.2 \text{ bar}$$

Consider constant volume process (2-3)

$$p_3 = \alpha \cdot p_2 = 1.5 \times 57.2 = 85.8 \text{ bar} = p_4$$

$$\frac{T_3}{T_2} = \frac{p_3}{p_2}; \qquad T_3 = 953.3 \times 1.5 = 1429.95 \text{ K}$$

Consider constant pressure process (3-4)

$$\frac{T_4}{T_3} = \frac{V_4}{V_3}; \qquad T_4 = 1429.95 \times 1.2 = 1715.94 \text{ K}$$

Consider isentropic process (4-5)

$$\frac{V_5}{V_4} = \frac{V_1}{V_4} = \frac{V_1/V_2}{V_4/V_2} = \frac{V_1/V_2}{V_4/V_3} = \frac{18}{1.2} = 15$$

$$T_5 = T_4\left(\frac{V_4}{V_5}\right)^{(\gamma-1)} = 1715.94\left(\frac{1}{15}\right)^{0.4} = 580.85 \text{ K}$$

Consider 1 kg of air i.e. m = 1 kg

Heat supplied, $Q_1 = Q_{2-3} + Q_{3-4} = m\,C_v\,(T_3 - T_2) + m\,C_p\,(T_4 - T_3)$

$= 1 \times 0.718\,(1429.95 - 953.3) + 1 \times 1.005\,(1715.94 - 1429.95)$

$= 342.235 + 287.420 = 629.655$ kJ/kg

Heat rejected, $Q_2 = Q_{5-1} = m\,C_v\,(T_5 - T_1)$

$= 1 \times 0.718 \times (580.85 - 300) = 201.650$ kJ/kg

Workdone W, $= Q_1 - Q_2 = 629.655 - 201.650 = 428.005$ kJ/kg

Thermal efficiency, $\eta = \frac{W}{Q_1} = \frac{428.005}{629.655} = \mathbf{0.6797 \text{ or } 67.97\%}$

(ii) Mean effective pressure, p_m in MPa

$$V_1 = \frac{mRT_1}{p_1} = \frac{1 \times 287 \times 300}{1 \times (10)^5} = 0.861 \text{ m}^3/\text{kg}$$

$$V_2 = \frac{V_1}{r} = \frac{0.861}{18} \text{ m}^3/\text{kg}$$

∴ Stroke volume, $V_s = V_1 - V_2 = 0.861 - \frac{0.861}{18} = 0.8132 \text{ m}^3/\text{kg}$

$$p_m = \frac{W}{V_s} = \frac{428.005}{0.8132} = 526.32 \text{ kPa} = \mathbf{0.52632 \text{ MPa}}$$
