

CONTENTS

KME 401 : APPLIED THERMODYNAMICS

UNIT-1 : INTRODUCTION

(1-1 A to 1-24 A)

Introduction to solid, liquid and gaseous fuels- Stoichiometry, exhaust gas analysis- First law analysis of combustion reactions- Heat calculations using enthalpy tables- Adiabatic flame temperature- Chemical equilibrium and equilibrium composition calculations using free energy. Introduction and Otto, Diesel and Dual cycles.

UNIT-2 : VAPOUR POWER CYCLES

(2-1 A to 2-35 A)

Vapour Power cycles: Vapor power cycles Rankine cycle with superheat, reheat and regeneration, exergy analysis. Rankine cycle, effect of pressure and temperature on Rankine cycle, Reheat cycle, Regenerative cycle, Feed water heaters, Binary vapour cycle, Combined cycles, Cogeneration.

Fuels and Combustion: Combustion analysis, heating values, air requirement, Air/Fuel ratio, standard heat of reaction and effect of temperature on standard heat of reaction, heat of formation, Adiabatic flame temperature.

UNIT-3 : BOILERS AND CONDENSER

(3-1 A to 3-30 A)

Boilers: Classifications and working of boilers, boiler mountings and accessories, Draught and its calculations, air pre-heater, feed water heater, super heater. Boiler efficiency, Equivalent evaporation. Boiler trial and heat balance.

Condenser: Classification of condenser, air leakage, condenser performance parameters.

UNIT-4 : NOZZLES & STEAM TURBINE

(4-1 A to 4-37 A)

Steam and Gas Nozzles: Flow through Convergent and convergent-divergent nozzles, variation of velocity, area and specific volume, choked flow, throat area, Nozzle efficiency, Off design operation of nozzle, Shock waves stationary normal shock waves, Effect of friction on nozzle, Super saturated flow.

Steam Turbines: Classification of steam turbine, Impulse and Reaction turbines, Staging, Stage and Overall efficiency, reheat factor, Bleeding, Velocity diagram of simple and compound multistage impulse and reaction turbines and related calculations, work done, efficiencies of reaction, Impulse reaction turbines, state point locus, Losses in steam turbines, Governing of turbines, Comparison with steam engine.

UNIT-5 : GAS TURBINE & JET PROPULSION

(5-1 A to 5-33 A)

Gas Turbine: Gas turbine classification, Brayton cycle, Principles of gas turbine, Gas turbine cycles with intercooling, reheat and regeneration and their combinations, Stage efficiency, Polytropic efficiency. Deviation of actual cycles from ideal cycles.

Jet Propulsion: Introduction to the principles of jet propulsion, Turbojet and turboprop engines and their processes, Principle of rocket propulsion, Introduction to Rocket Engine. Reciprocating compressors, staging of reciprocating compressors, optimal stage pressure ratio, effect of intercooling, minimum work for multistage reciprocating compressors.

SHORT QUESTIONS

(SQ-1A to SQ-13A)

SOLVED PAPERS (2014-15 TO 2018-19)

(SP-1A to SP-17A)

1

UNIT

Introduction

CONTENTS

Part-1	: Introduction to Solid, Liquid and Gaseous Fuels	1-2A to 1-3A
Part-2	: Stoichiometry	1-3A to 1-4A
Part-3	: Exhaust Gas Analysis	1-4A to 1-5A
Part-4	: First Law Analysis of Combustion Reactions, Heat Calculations using Enthalpy Tables	1-5A to 1-7A
Part-5	: Adiabatic Flame Temperature	1-7A to 1-7A
Part-6	: Chemical Equilibrium and Equilibrium Composition Calculations using Free Energy	1-7A to 1-10A
Part-7	: Introduction to Otto Cycle	1-10A to 1-14A
Part-8	: Diesel Cycle	1-14A to 1-18A
Part-9	: Dual Cycle	1-18A to 1-23A

PART-1*Introduction to Solid, Liquid and Gaseous Fuels.***CONCEPT OUTLINE**

Fuels : A fuel is a substance which releases heat energy on combustion. The principal combustible elements of each fuel are carbon and hydrogen.

Questions-Answers**Long Answer Type and Medium Answer Type Questions**

Que 1.1. Write short note on following :

- a. Solid Fuels,
- b. Liquid Fuels, and
- c. Gaseous Fuels.

Answer**a. Solid Fuels :**

1. Solid fuels refer to various types of solid materials that are used as fuel to produce energy and provide heat, usually released through combustion.
2. Wood, charcoal, peat, coke, etc are the some examples of solid fuel.

b. Liquid Fuels :

1. Liquid fuels are those combustible or energy generating molecules that can be harnessed to create mechanical energy, usually producing kinetic energy.
2. Diesel, petrol, kerosene, biodiesel, ethanol are the some examples of liquid fuels.

c. Gaseous Fuels :

1. Gaseous fuels are those substances that burn in air and releases heat.
2. Natural gas, liquefied petroleum gas and coal gas are the some examples of gaseous fuels.

Que 1.2. What are the advantages and disadvantages of liquid fuels over solid fuels ?

Answer**A. Advantages of Liquid Fuels over Solid Fuels :**

1. Require less space for storage.
2. Higher calorific value.
3. Easy handling and transportation.
4. Better control of consumption by using valves and number of burners.
5. Absence of danger from spontaneous combustion.
6. Better cleanliness and absence from dust.
7. No ash problem.
8. No problem of corrosion and deterioration during storage.
9. Higher efficiency.
10. Less number of staff required.

B. Disadvantages of Liquid Fuels over Solid Fuels :

1. Higher cost.
2. Greater risk of fire.
3. Require costly containers for storage and transportation.

PART-2*Stoichiometry.***CONCEPT OUTLINE**

Stoichiometry : It is the part of chemistry that studies amount of substances that are involved in reactions.

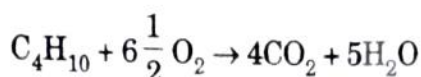
Questions-Answers**Long Answer Type and Medium Answer Type Questions**

Que 1.3. Explain stoichiometry of combustion.

Answer

1. Stoichiometric combustion takes place in a stoichiometric mixture of a fuel and oxygen.
2. A stoichiometric mixture of a fuel and oxygen contains the precise amount of oxygen to completely burn out all the combustible elements present in the fuel.

3. This implies conversion of all C content to CO_2 and all H content to H_2O .
4. There is neither an excess nor deficiency of oxygen present in the reaction mixture.
5. As a result, there is no free oxygen in the reaction products, while all the combustibles in the fuel are completely oxidized. For instance, the stoichiometric combustion of *n*-butane is



6. The equation is balanced with respect to all elements and presents the precise amount of oxygen in the reactants just sufficient to ensure a complete burning of the fuel.
7. Stoichiometric combustion is essentially a theoretical reaction.

PART-3

Exhaust Gas Analysis.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 1.4. Explain the working procedure of Orsat apparatus for exhaust gas analysis.

Answer

1. 100 cm^3 of gas whose analysis is to be made is drawn into the bottle by lowering the leveling bottle.
2. The stop cock S_4 is then opened and the whole flue gas is forced to pipette 1. The gas remains in this pipette for some time and most of the carbon dioxide is absorbed.
3. The leveling bottle is then lowered to allow the chemical to come to its original level.
4. The volume of gas thus absorbed is read on the scale of the measuring bottle.
5. The flue gas is then forced through the pipette 1 for a number of times to ensure that the whole of the CO_2 is absorbed.
6. Further, the remaining flue gas is then forced to the pipette 2 which contains pyrogalllic acid to absorb whole of O_2 .
7. The reading on the measuring burette will be the sum of volume of CO_2 and O_2 .
8. The oxygen content can then be found out by subtraction.

Applied Thermodynamics

9. Finally, as before, the sample of gas is forced through the pipettes 3 and 4 to absorb carbon monoxide completely.

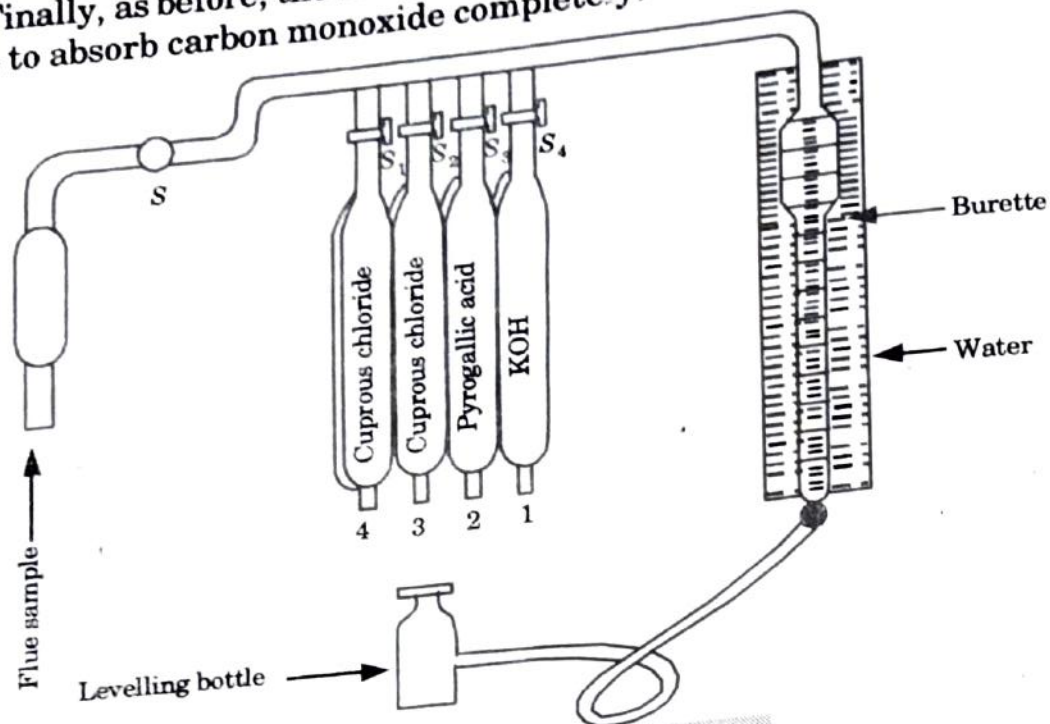


Fig. 1.4.1. Orsat apparatus.

10. The amount of nitrogen in the sample can be determined by subtracting from total volume of gas the sum of CO_2 , and CO and O_2 contents.

PART-4

First Law Analysis of Combustion Reactions, Heat Calculations using Enthalpy Tables.

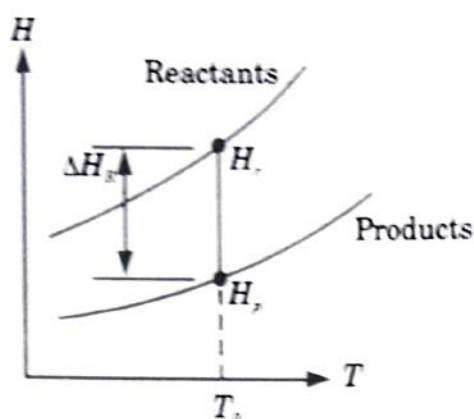
Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 1.5. How first law of thermodynamics help in analysis of combustion reactions ?

Answer

1. Consider a steady flow system as shown in Fig. 1.5.1. Let reactant at temperature T_0 and pressure p_0 enter a combustion chamber where combustion takes place and heat is transferred to surrounding and the products of combustion leave at T_0 and p_0 .

Fig. 1.5.1. Definition of ΔH_R .

2. According to steady flow process,

$$(Q - W)_{T_0} = (H_p - H_r)_{T_0} = (\Delta H_R)_{T_0}$$

3. If $W = 0$,

$$(\Delta H_R)_{T_0} = (H_p - H_r)_{T_0} = (Q)_{T_0}$$

Where,

$(H_p)_{T_0}$ = Enthalpy of product at T_0 ,

$(H_r)_{T_0}$ = Enthalpy of reaction at T_0, p_0 and

$(Q)_{T_0}$ = Heat of reaction.

4. If $H_p > H_r$, then Q will be positive and heat is absorbed by the system and reaction is called endothermic.
5. If $H_p < H_r$, then Q will be negative and heat is released by the system and reaction is called exothermic.

Que 1.6. ΔH_0 (enthalpy of combustion at reference temperature T_0) for benzene vapour (C_6H_6) at $25^\circ C$ is -3301000 kJ/mole with the H_2O in the liquid phase. Calculate ΔH_0 for the H_2O in the vapour phase.

Answer

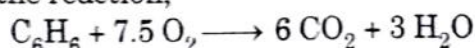
1. If H_2O remains as a vapour, the heat transferred to the surroundings will be less than when the vapour condenses by the amount due to the change in enthalpy of the vapour during condensation at the reference temperature.

$$\therefore \Delta H_0 (\text{vapour}) = \Delta H_0 (\text{liquid}) + m_s h_{fg0}$$

Where, m_s = Mass of H_2O formed, and

h_{fg0} = Change in enthalpy of steam between saturated liquid and saturated vapour at the reference temperature T_0 .
 $= 2441.8 \text{ kJ at } 25^\circ C$

2. For the reaction,



Applied Thermodynamics

3. 3 moles of H_2O are formed on combustion of 1 mole of C_6H_6 , so mass of water is,

$$m_s = 3 \times 18 = 54 \text{ kg}$$

$$\therefore \Delta H_0 (\text{vapour}) = -3301000 + 54 \times 2441.8 = -3169143 \text{ kJ/mole}$$

PART-5*Adiabatic Flame Temperature.***Questions-Answers****Long Answer Type and Medium Answer Type Questions**

Que 1.7. Define adiabatic flame temperature and state its importance.

Answer**A. Adiabatic Flame Temperature :**

1. If there is a negligible change in potential and kinetic energies during a combustion process then in the absence of any work interactions, the liberated heat is partly lost to the surroundings and the balance is consumed up internally raising the temperature of the combustion products.
2. Such a condition arises during a steady flow as well as non-flow combustion process.
3. In the limiting case, when there is no heat loss to the surroundings ($Q = 0$), the temperature of the combustion products reaches a maximum called the adiabatic flame temperature. It is also called adiabatic combustion temperature.

B. Importance of Adiabatic Flame Temperature :

1. It is used to characterize the quality of fuel.
2. It is used to determine suitability of fuel for an application.
3. It is used to determine extent of substitution of a lower quality fuel to converse higher quality fuel.
4. It is very important in design and scale up procedures wherever heat transfer is a significant consideration.

PART-6*Chemical Equilibrium and Equilibrium Composition Calculations using Free Energy.*

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 1.8. Define chemical equilibrium and Gibbs free energy.

Answer

A. Chemical Equilibrium :

1. Chemical equilibrium is said to be in force in a system if there is no tendency for a net chemical reaction to occur within the system. Such a system is chemically homogeneous throughout and no change occurs in its chemical composition over time.

2. For a chemical process to occur,

$$\Delta s_{\text{universe}} = \Sigma \Delta s_{\text{sys}} + \Delta s_{\text{surr}} \geq 0$$

3. For a chemical reaction that will never occur,

$$\Delta s_{\text{universe}} = \Sigma \Delta s_{\text{sys}} + \Delta s_{\text{surr}} < 0$$

B. Gibbs Free Energy :

1. The energy associated with a chemical reaction that can be used to work is called Gibbs free energy.
2. It is given as the sum of enthalpy of system plus the product of temperature and entropy of the system.

$$G = H - Ts$$

Que 1.9. What is general criterion of equilibrium for a non-flow and flow process ?

Answer

A. General Criterion of Equilibrium for a Non-flow Process :

1. Equilibrium for a non-flow process can be developed from the concept of entropy generation.
2. If there occurs an infinitesimally small heat transfer δQ into a system with an instantaneous temperature T , then the entropy generation of the system is given by

$$Tds - \delta Q = T\delta s_{\text{gen}}$$

3. From the second law, δs_{gen} must be positive or zero.

$$\therefore Tds - \delta Q = T\delta s_{\text{gen}} \geq 0$$

Applied Thermodynamics

B. General Criterion of Equilibrium for a Flow Process :

1. For an adiabatic, steady flow process, the net entropy generation in the control volume is,

$$s_{\text{gen, CV}} = \sum n_p s_p - \sum n_R s_R$$

Where, n stands for number of moles, CV in the subscript for control

volume, P for products, and R for the reactants.

2. Now apply eq. (1.10.2), if the heat interaction takes place between the control volume and the surroundings, then the entropy generation will be

$$S_{\text{gen, CV}} = \sum n_p s_p - \sum n_R s_R - Q/T_o$$

Que 1.10.

Define equilibrium constant. Also write down the effect

of total system pressure on equilibrium composition.

Answer**A. Equilibrium Constant :**

1. The equilibrium constant K_p defined by partial pressures of the total species involved in the chemical equilibrium is independent of the total pressure of the system. It depends upon the temperature of the system.
2. The equilibrium constant K_p can also be expressed in mole fraction terms as given below,

$$p_A = x_A P, \quad p_B = x_B P, \quad p_E = x_E P, \quad p_F = x_F P$$

$$K_p = \left[\frac{X_E^e X_F^f}{X_A^a X_B^b} \right] (P)^{(e+f)-(a+b)}$$

Where, x represents the mole fraction of a particular component given in the subscript.

B. Effect of Total System Pressure on Equilibrium Composition :

1. For any given reaction, the equilibrium constant K_p is constant at a particular temperature because K_p is a function only of temperature for a specified reaction.
2. However, the equilibrium composition may or may not vary with the system pressure P .
3. From the formula of K_p , we have P is raised to the power $(e + f + \dots) - (a + b + \dots)$. This gives us following three cases :

Case I : If $(e + f + \dots) - (a + b + \dots) = 0$, a change in pressure will not affect the equilibrium composition.

Case II : If $(e + f + \dots) - (a + b + \dots) > 0$, an increase in pressure will bring about a decrease in the product concentration, while a decrease in

pressure will increase products concentrations at the equilibrium. This is must to keep K_p constant at the equilibrium temperature.

Case III : If $(e + f + \dots) - (a + b + \dots) < 0$, an increase in pressure will bring about an increase in the product concentration while a decrease in pressure will decrease product concentrations at the equilibrium.

Que 1.11.

Determine the standard free energy change for the following combustion reaction :

$\text{CH}_4(\text{gas}) + 2\text{O}_2(\text{gas}) \rightarrow \text{CO}_2(\text{gas}) + 2\text{H}_2\text{O}(\text{liq})$ at 298 K using the following data :

Thermodynamic parameter	CH_4 (gas)	O_2 (gas)	CO_2 (gas)	H_2O (gas)
ΔS° (cal K^{-1} kmol^{-1})	44.5	49.0	51.06	16.75
ΔH_f° (kcal kmol^{-1})	17.9		-94.0	-68.3

Answer

- Enthalpy change, $\Delta H^\circ = \sum (\Delta H_f^\circ)_{\text{products}} - \sum (\Delta H_f^\circ)_{\text{reactants}}$
 $= [(2) (-68.3) + (1) (-94)] - [(1) (17.9) + (2) (0)]$
 $= -212.7 \text{ kcal kmol}^{-1} \text{ of } \text{CH}_4 \text{ burnt}$
- Entropy change, $\Delta S^\circ = \sum (\Delta S_f^\circ)_{\text{products}} - \sum (\Delta S_f^\circ)_{\text{reactants}}$
 $= [(2) (16.75) + (1) (51.06)] - [(1) (44.5) + (2) (49)]$
 $= -57.94 \text{ cal K}^{-1} \text{ kmol}^{-1} \text{ of } \text{CH}_4 \text{ burnt}$
 $= -0.05794 \text{ kcal K}^{-1} \text{ kmol}^{-1} \text{ of } \text{CH}_4 \text{ burnt}$
- The standard free energy change is given as,
 $\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$
 $= -212.7 - (298) (-0.05794)$
 $= -195.43388 \text{ kcal kmol}^{-1} \text{ of } \text{CH}_4 \text{ burnt}$

PART-7*Introduction to Otto Cycle.***Questions-Answers****Long Answer Type and Medium Answer Type Questions**

Que 1.12.

Derive an expression for air standard efficiency of Otto cycle in terms of compression ratio.

AKTU 2018-19, Marks 10

Answer

1. It is a constant volume cycle which is mainly used in petrol engine.
2. p - v and T - s diagrams are shown in Fig. 1.12.1(a) and (b) respectively.
3. This cycle consists of four processes :

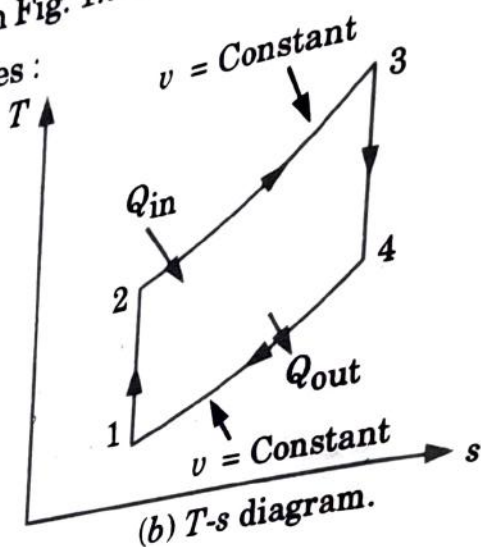
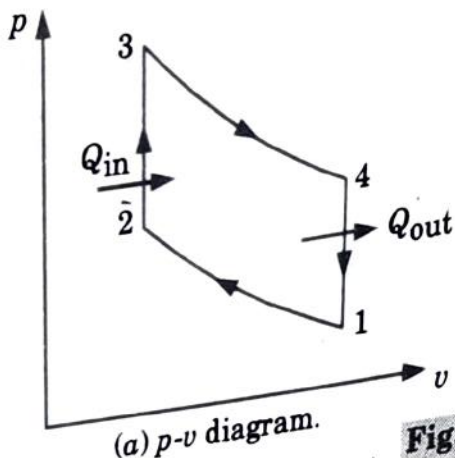


Fig. 1.12.1.

a. Process (1-2) :

1. It is isentropic compression.

2. Ratio of v_1 and v_2 is known as compression ratio and it is denoted by r

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

Where,

v_1 = Volume at start of compression.

v_2 = Volume at end of compression.

3. Now,

$$p_1 v_1^\gamma = p_2 v_2^\gamma$$

$$p_2 = p_1 \left(\frac{v_1}{v_2} \right)^\gamma = p_1 r^\gamma$$

- b. Process (2-3) :** It is heat addition process. Heat is added during this process at constant volume.

$$Q_{in} = C_v (T_3 - T_2)$$

- c. Process (3-4) :** It is isentropic expansion.

$$p_3 v_3^\gamma = p_4 v_4^\gamma$$

$$p_4 = p_3 \left(\frac{v_3}{v_4} \right)^\gamma$$

$$= \frac{p_3}{r^\gamma} \quad \left\{ \because \frac{v_4}{v_3} = \frac{v_1}{v_2} = r \right\}$$

- d. **Process (4-1)** : It is heat rejection process. Heat is rejected during this process at constant volume.

$$Q_{\text{out}} = C_v(T_4 - T_1)$$

4. Work done (W) = Heat added – Heat rejected

$$= C_v(T_3 - T_2) - C_v(T_4 - T_1)$$

5. Thermal efficiency, $\eta = \frac{\text{Work done}}{\text{Heat input}}$

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

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

$$= 1 - \frac{T_4 - T_1}{T_3 - T_2} \quad \dots(1.12.1)$$

6. Now, process 1-2 and 3-4 are adiabatic, so

$$\begin{aligned} \frac{T_2}{T_1} &= \left(\frac{v_1}{v_2} \right)^{\gamma-1} \\ &= (r)^{\gamma-1} \end{aligned}$$

$$\therefore T_2 = T_1 (r)^{\gamma-1}$$

And,
$$\begin{aligned} \frac{T_3}{T_4} &= \left(\frac{v_4}{v_3} \right)^{\gamma-1} \\ &= (r)^{\gamma-1} \end{aligned}$$

$$\therefore T_3 = T_4 (r)^{\gamma-1}$$

7. Putting these values in eq. (1.12.1), we have

$$\eta = 1 - \frac{T_4 - T_1}{T_4(r)^{\gamma-1} - T_1(r)^{\gamma-1}}$$

$$= 1 - \frac{T_4 - T_1}{(T_4 - T_1)r^{\gamma-1}}$$

$$\eta = 1 - \frac{1}{r^{\gamma-1}}$$

Que 1.13. Derive an expression for mean effective pressure for Otto cycle.

Answer

1. The net work output for an Otto cycle can be expressed as,

Applied Thermodynamics

$$W = \frac{p_3 v_3 - p_4 v_4}{\gamma - 1} - \frac{p_2 v_2 - p_1 v_1}{\gamma - 1}$$

2. We know that, $\frac{p_2}{p_1} = \frac{p_3}{p_4} = r^\gamma$

$$\frac{p_3}{p_2} = \frac{p_4}{p_1} = \alpha \text{ (say)}$$

Also, $v_1 = r v_2$ and $v_4 = r v_3$

$$\begin{aligned} \therefore W &= \frac{p_1 v_1}{\gamma - 1} \left(\frac{p_3 v_3}{p_1 v_1} - \frac{p_4 v_4}{p_1 v_1} - \frac{p_2 v_2}{p_1 v_1} + 1 \right) \\ &= \frac{p_1 v_1}{\gamma - 1} \left(\frac{\alpha r^\gamma}{r} - \alpha - \frac{r^\gamma}{r} + 1 \right) = \frac{p_1 v_1}{\gamma - 1} (\alpha r^{\gamma-1} - \alpha - r^{\gamma-1} + 1) \\ &= \frac{p_1 v_1}{\gamma - 1} [(\alpha - 1)(r^{\gamma-1} - 1)] \end{aligned}$$

3. Swept volume $= v_1 - v_2 = v_2(r - 1)$

4. The mean effective pressure of the cycle is given by

$$p_m = \frac{\text{Work output}}{\text{Swept volume}}$$

$$p_m = \frac{\frac{1}{\gamma - 1} p_1 v_1 [(\alpha - 1)(r^{\gamma-1} - 1)]}{v_2(r - 1)} = \frac{p_1 r [(\alpha - 1)(r^{\gamma-1} - 1)]}{(\gamma - 1)(r - 1)}$$

Que 1.14. Determine thermal efficiency and mean effective pressure of thermodynamic cycle used by a 4-stroke petrol engine. Details of cycle are as follows :

Compression ratio = 7

Initial state = 100 kPa and 90 °C

Swept volume = 0.1 m³

Heat added to cycle at constant volume = 100 kJ/cycle

Consider air as working fluid.

AKTU 2018-19, Marks 10

Answer

Given : $r = 7$, $p_1 = 100$ kPa, $T_1 = 90$ °C, $v_{\text{swept}} = 0.1$ m³,
Heat added at constant volume = 100 kJ/cycle

To Find : i. Thermal efficiency.
ii. Mean effective pressure.

1. Thermal efficiency, $\eta = 1 - \frac{1}{r^{\gamma-1}}$

$$= 1 - \frac{1}{7^{1.4-1}} = 0.541 \quad (\text{For air, } \gamma = 1.4)$$

$$\begin{aligned} 2. \quad \text{Work done/kg/cycle} &= \text{Heat added/kg/cycle} \times \eta \\ &= 100 \times 0.541 \\ &= 54.1 \text{ kJ} \end{aligned}$$

$$\begin{aligned} 3. \quad \text{Mean effective pressure} &= \frac{\text{Work done}}{\text{Swept volume}} \\ &= \frac{54.1}{0.1} \text{ kJ/m}^3 = 541 \text{ kN/m}^2 = 5.41 \text{ bar} \end{aligned}$$

PART-8

Diesel Cycle.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 1.15. Sketch the diesel cycle on $p-v$ and $T-s$ diagram and derive the expression for the efficiency of diesel cycle.

Answer

1. It is a constant pressure cycle which is mainly used in diesel engine.

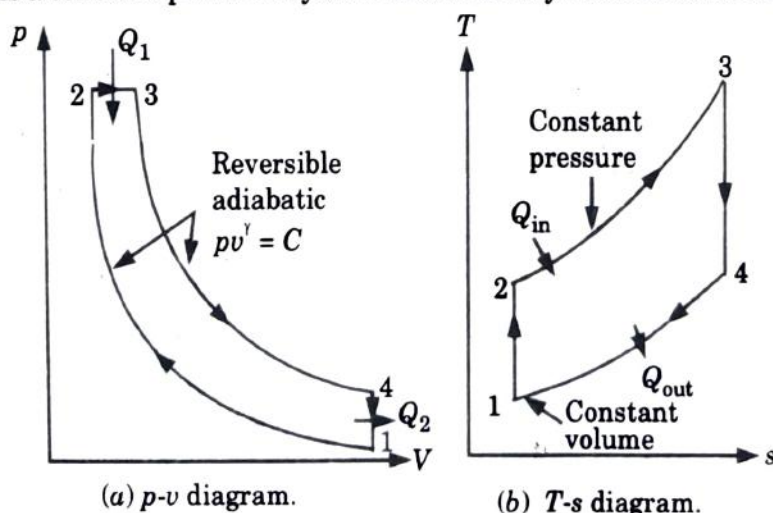


Fig. 1.15.1.

2. $p-v$ and $T-s$ diagram of this cycle are shown in Fig. 1.15.1(a) and (b) respectively. This cycle consists of following processes :

- a. **Process (1-2) :** It is isentropic compression process.

$$p_1 v_1^\gamma = p_2 v_2^\gamma$$

- b. **Process (2-3)** : It is constant pressure process and heat is added at constant pressure.

$$Q_{in} = C_p(T_3 - T_2)$$

- c. **Process (3-4)** : It is isentropic expansion process.

$$p_3 v_3^\gamma = p_4 v_4^\gamma$$

- d. **Process (4-1)** : It is constant volume process and heat is rejected at constant volume.

$$Q_{out} = C_v(T_4 - T_1)$$

3. Work done during the cycle,

$$\begin{aligned} W &= \text{Heat added} - \text{Heat rejected} \\ &= C_p(T_3 - T_2) - C_v(T_4 - T_1) \end{aligned}$$

4. Thermal efficiency, $\eta = \frac{\text{Work done}}{\text{Heat input}}$

$$\begin{aligned} &= \frac{C_p(T_3 - T_2) - C_v(T_4 - T_1)}{C_p(T_3 - T_2)} = 1 - \frac{C_v(T_4 - T_1)}{C_p(T_3 - T_2)} \\ &= 1 - \frac{T_1 \left(\frac{T_4}{T_1} - 1 \right)}{\gamma T_2 \left(\frac{T_3}{T_2} - 1 \right)} \quad \left(\because \frac{C_p}{C_v} = \gamma \right) \quad \dots(1.15.1) \end{aligned}$$

5. For reversible isentropic compression and expansion processes,

$$\frac{T_1}{T_2} = \left(\frac{v_2}{v_1} \right)^{\gamma-1} \quad \dots(1.15.2)$$

$$\frac{T_4}{T_3} = \left(\frac{v_3}{v_4} \right)^{\gamma-1} \quad \dots(1.15.3)$$

6. For constant pressure heat addition

$$\frac{T_3}{T_2} = \frac{v_3}{v_2} = \rho \text{ (cut-off ratio)} \quad \dots(1.15.4)$$

7. From eq. (1.15.2) and eq. (1.15.3), we get

$$\frac{T_4}{T_1} = \frac{T_3}{T_2} \left(\frac{v_3}{v_4} \right)^{\gamma-1} \left(\frac{v_4}{v_2} \right)^{\gamma-1} \left(\frac{v_2}{v_1} \right)^{\gamma-1}$$

8. For constant volume process,

$$v_4 = v_1$$

$$\frac{T_4}{T_1} = \frac{v_3}{v_2} \left(\frac{v_3}{v_2} \right)^{\gamma-1} = \left(\frac{v_3}{v_2} \right)^\gamma$$

9. Substituting these values in eq. (1.15.1), we get

$$\dots(1.15.5)$$

$$\eta = 1 - \frac{1}{\gamma \left(\frac{v_1}{v_2} \right)^{\gamma-1}} \left(\frac{\left(\frac{v_3}{v_2} \right)^{\gamma} - 1}{\frac{v_3}{v_2} - 1} \right)$$

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

Que 1.16. Derive an expression for mean effective pressure for diesel cycle.

Answer

1. The net work output for a diesel cycle is given by,

$$\begin{aligned} W &= p_2(v_3 - v_2) + \frac{p_3 v_3 - p_4 v_4}{\gamma - 1} - \frac{p_2 v_2 - p_1 v_1}{\gamma - 1} \\ &= p_2 v_2 (\rho - 1) + \frac{p_3 \rho v_2 - p_4 r v_2}{\gamma - 1} - \frac{p_2 v_2 - p_1 r v_2}{\gamma - 1} \\ &\quad \left[\because \frac{v_3}{v_2} = \rho \text{ and } \frac{v_1}{v_2} = r, \quad v_4 = v_1, \quad v_r = r v_2 \right] \\ &= v_2 \left[\frac{p_2 (\rho - 1) (\gamma - 1) + p_3 \rho - p_4 r - (p_2 - p_1 r)}{\gamma - 1} \right] \\ &= v_2 \left[\frac{p_2 (\rho - 1) (\gamma - 1) + p_3 \left(\rho - \frac{p_4}{p_3} r \right) - p_2 \left(1 - \frac{p_1}{p_2} r \right)}{\gamma - 1} \right] \\ &= \frac{p_2 v_2 [(\rho - 1) (\gamma - 1) + \rho - \rho^{\gamma} r^{1-\gamma} - (1 - r^{1-\gamma})]}{\gamma - 1} \\ &\quad \left[\because \frac{p_4}{p_3} = \left(\frac{v_3}{v_4} \right)^{\gamma} = \left(\frac{\rho}{r} \right)^{\gamma} = \rho^{\gamma} r^{-\gamma} \right] \\ &= \frac{p_1 v_1 r^{\gamma-1} [(\rho - 1) (\gamma - 1) + \rho - \rho^{\gamma} r^{1-\gamma} - (1 - r^{1-\gamma})]}{\gamma - 1} \\ &\quad \left[\because \frac{p_2}{p_1} = \left(\frac{v_1}{v_2} \right)^{\gamma} \text{ or } p_2 = p_1 r^{\gamma} \text{ and } \frac{v_1}{v_2} = r \text{ or } v_2 = v_1 r^{-1/\gamma} \right] \\ &= \frac{p_1 v_1 r^{(\gamma-1)} [\gamma (\rho - 1) - r^{(1-\gamma)} (\rho^{\gamma} - 1)]}{\gamma - 1} \end{aligned}$$

2. Swept volume = $v_1 \left(\frac{r-1}{r} \right)$

3. The expression for mean effective pressure can be obtained as,

$$p_m = \frac{p_1 v_1 r^{(\gamma-1)} [\gamma(\rho-1) - (\rho^\gamma - 1)]}{(\gamma-1) v_1 \left(\frac{r-1}{r} \right)}$$

$$= \frac{p_1 r^\gamma [\gamma(\rho-1) - r^{(1-\gamma)}(\rho^\gamma - 1)]}{(\gamma-1)(r-1)}$$

Que 1.17. In an air standard diesel cycle with compression ratio 14, the conditions of air at start of compression stroke are 1 bar, 300 K. After addition of heat at constant pressure, the temperature rises to 2775 K. Determine the thermal efficiency of the cycle, net work done per kg of air and the mean effective pressure.

(Take : $R = 287 \text{ J/kg K}$ and $\gamma = 1.4$)

AKTU 2017-18, Marks 10

Answer

Given : $r = 14$, $p_1 = 1 \text{ bar}$, $T_1 = 300 \text{ K}$, $T_3 = 2775 \text{ K}$,

$R = 287 \text{ J/kg K}$, $\gamma = 1.4$

To Find :

- Thermal efficiency of cycle.
- Net work done per kg of air.
- Mean effective pressure.

1. From ideal gas equation,

$$v_4 = v_1 = \frac{RT_1}{p_1} = \frac{287 \times 300}{1 \times 10^5} = 0.861 \text{ m}^3/\text{kg}$$

$$v_2 = v_1/r = \frac{0.861}{14} = 0.0615 \text{ m}^3/\text{kg}$$

2. For isentropic process 1-2,

$$p_1 v_1^\gamma = p_2 v_2^\gamma$$

$$p_2 = p_1 \left(\frac{v_1}{v_2} \right)^\gamma = p_1 (r)^\gamma$$

$$= 1 \times (14)^{1.4} = 40.23 \text{ bar}$$

Also,

$$\frac{T_2}{T_1} = \left(\frac{v_1}{v_2} \right)^{\gamma-1} = (14)^{1.4-1} = 2.874$$

$$T_2 = T_1 \times 2.874 = 300 \times 2.874 = 862.2 \text{ K}$$

3. For isobaric process 2-3,

$$\frac{v_2}{T_2} = \frac{v_3}{T_3}$$

$$v_3 = \frac{T_3}{T_2} \times v_2 = \frac{2775}{862.2} \times 0.0615 = 0.198$$

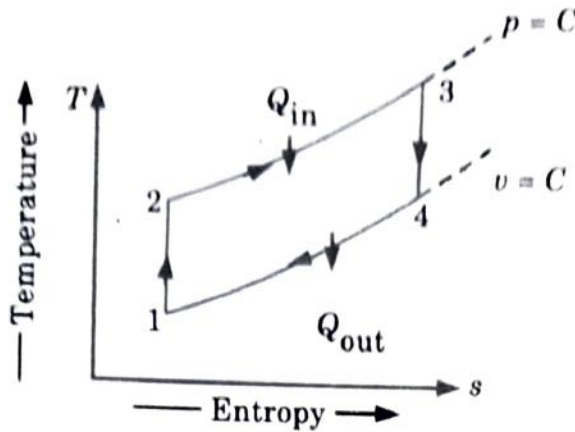


Fig. 1.17.1.

4. For isentropic process 3-4,

$$\frac{T_3}{T_4} = \left(\frac{v_4}{v_3} \right)^{\gamma-1} = \left(\frac{v_1}{v_3} \right)^{\gamma-1} = \left(\frac{0.861}{0.198} \right)^{1.4-1} = 1.8$$

$$T_4 = \frac{T_3}{1.8} = \frac{2775}{1.8} = 1541.67 \text{ K}$$

5. Thermal efficiency of the cycle,

$$\begin{aligned} \eta &= 1 - \frac{(T_4 - T_1)}{\gamma(T_3 - T_2)} = 1 - \frac{(1541.67 - 300)}{1.4(2775 - 862.2)} \\ &= 1 - \frac{1241.67}{267792} = 0.5363 \text{ or } 53.63 \% \end{aligned}$$

6. Also,

$$\eta = \frac{\text{Work done (W)}}{\text{Heat supplied (Q}_{in})}$$

$$\begin{aligned} W &= \eta \times Q_{in} = \eta \times C_p(T_3 - T_2) \\ &= 0.5363 \times 1.005(2775 - 862.2) \end{aligned}$$

[For air, $C_p = 1.005 \text{ kJ/kg K}$]

$$= 1030.96 \text{ kJ/kg}$$

7. Mean effective pressure,

$$\begin{aligned} p_m &= \frac{\text{Work done}}{\text{Swept volume}} = \frac{W}{v_2(r-1)} \\ &= \frac{1030.96 \times 10^3}{0.0615 \times (14 - 1)} = 12.895 \times 10^5 \text{ N/m}^2 \\ &= 12.895 \text{ bar} \end{aligned}$$

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 1.18. Derive an expression for the efficiency of dual cycle with $p-v$ and $T-s$ diagram.

Answer

1. Dual cycle is most suitable for high speed engine. Some part of heat addition takes place at constant volume (2-3) and rest of the part takes place at constant pressure (3-4) as shown in Fig. 1.18.1(a).
2. Heat rejection takes place in process (5-1) at constant volume.
3. This cycle is called dual cycle because it has the features of both Otto cycle and diesel cycle.

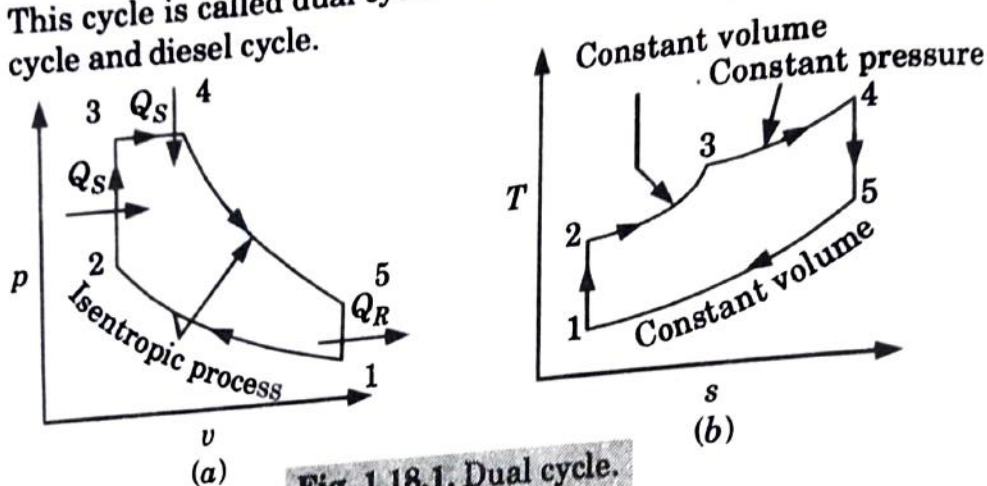


Fig. 1.18.1. Dual cycle.

4. For dual cycle,

Total heat supplied = Heat supplied at constant volume (2-3) + Heat supplied at constant pressure (3-4)

$$= C_v(T_3 - T_2) + C_p(T_4 - T_3)$$

Heat rejection = Heat rejected at constant volume in process (5-1)

$$= C_v(T_5 - T_1)$$

5. Thermal efficiency,

$$\eta = \frac{\text{Total heat supplied} - \text{Heat rejected}}{\text{Total heat supplied}}$$

$$= \frac{C_v(T_3 - T_2) + C_p(T_4 - T_3) - C_v(T_5 - T_1)}{C_v(T_3 - T_2) + C_p(T_4 - T_3)}$$

$$= 1 - \frac{(T_5 - T_1)}{(T_3 - T_2) + \gamma(T_4 - T_3)} \left\{ \because \frac{C_p}{C_v} = \gamma \right\} \dots (1.18.1)$$

6. We know that, $T_2 = T_1 \left(\frac{v_1}{v_2} \right)^{\gamma-1} = T_1 r^{\gamma-1}$

(r = Compression ratio = v_1/v_2)

$$T_3 = T_2 \frac{p_3}{p_2} = T_1 r^{\gamma-1} \alpha \quad (\alpha = \text{Pressure ratio} = p_3/p_2)$$

$$T_4 = T_3 \frac{v_4}{v_3} = T_1 r^{\gamma-1} \alpha \rho \quad (\rho = \text{Cut-off ratio} = v_4/v_3)$$

Also, $T_5 = T_4 \left(\frac{v_4}{v_5} \right)^{\gamma-1} = T_1 r^{\gamma-1} \alpha \rho \left(\frac{v_4}{v_5} \right)^{\gamma-1}$

$$\therefore \frac{v_4}{v_5} = \frac{v_4}{v_1} = \frac{v_4 v_3}{v_3 v_1} = \frac{v_4 v_2}{v_3 v_1} \quad (\because v_5 = v_1 \text{ and } v_2 = v_3)$$

$$\therefore \frac{v_4}{v_5} = \frac{\rho}{r}$$

7. Substituting all these values in eq. (1.18.1), we get

$$\eta = 1 - \frac{T_1 r^{\gamma-1} \alpha \rho \left(\frac{v_4}{v_5} \right)^{\gamma-1} - T_1}{(T_1 r^{\gamma-1} \alpha - T_1 r^{\gamma-1}) + \gamma (T_1 r^{\gamma-1} \alpha \rho - T_1 r^{\gamma-1} \alpha)}$$

$$\eta = 1 - \frac{1}{r^{\gamma-1}} \left[\frac{\alpha \rho^{\gamma} - 1}{(\alpha - 1) + \alpha \gamma (\rho - 1)} \right]$$

Que 1.19. Compare the Otto, diesel and dual cycle.

Answer

Comparison between these cycles is done on the basis of following point :

a. **Same Compression Ratio and Heat Addition :**

1. For the same compression ratio and heat addition Otto, diesel and dual cycle are represented in Fig. 1.19.1 on the $p-v$ and $T-s$ diagram as :

Otto cycle : 1 - 2 - 3 - 4 - 1

Diesel cycle : 1 - 2 - 3' - 4' - 1

Dual cycle : 1 - 2 - 2'' - 3'' - 4'' - 1

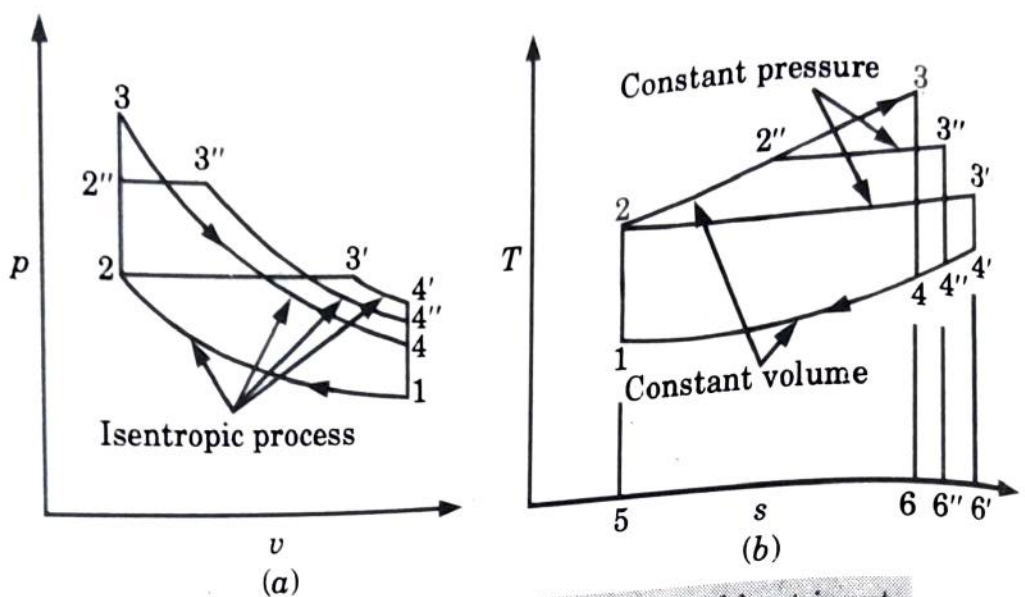


Fig. 1.19.1. Same compression ratio and heat input.

2. Now from the $T-s$ diagram, it is clear that,

$$\text{Area } 5-2-3-6 = \text{Area } 5-2-3'-6' = \text{Area } 5-2-2''-3''-6''.$$

3. This represents the heat input. So every cycle has same heat input for same compression ratio which is represented by $1 \rightarrow 2$.
4. So, Otto cycle has highest efficiency. Diesel cycle has least efficiency while dual cycle has efficiency between diesel and Otto cycles.

$$\therefore \eta_{\text{Otto}} > \eta_{\text{Dual}} > \eta_{\text{Diesel}}$$

b. Same Compression Ratio and Heat Rejection :

1. In Fig. 1.19.2, Otto and diesel cycle are shown. Efficiency of both the cycle is given as,

$$\eta_{\text{Otto}} = 1 - \frac{Q_R}{Q_S}$$

$$\eta_{\text{Diesel}} = 1 - \frac{Q_R}{Q'_S}$$

2. Q_S is heat supplied in Otto cycle and equal to the area under the curve $2 \rightarrow 3$ on $T-s$ diagram.
3. Q'_S is heat supplied in diesel cycle and equal to the area under the curve $2 \rightarrow 3'$ on $T-s$ diagram.
4. From $T-s$ diagram, it is clear that,

$$Q_S > Q'_S$$

$$(\text{Heat supplied})_{\text{Otto cycle}} > (\text{Heat supplied})_{\text{Diesel cycle}}$$

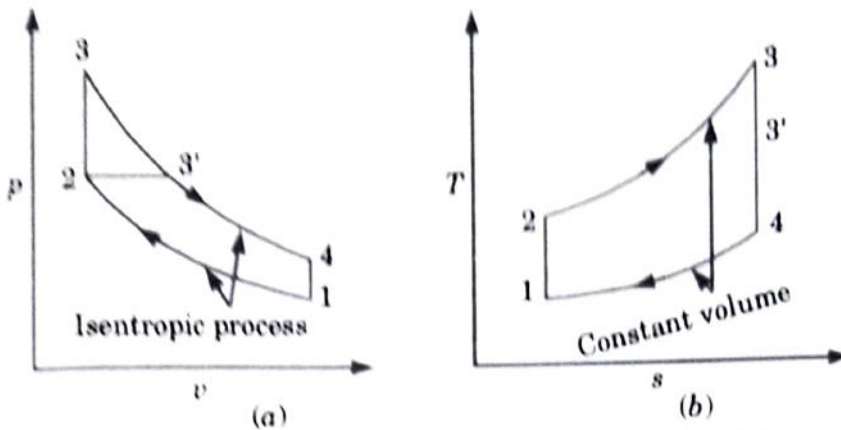


Fig. 1.19.2. Same compression ratio and heat rejection.

5. So, efficiency of Otto cycle is greater than that of diesel cycle and we can conclude that,

$$\eta_{\text{Otto}} > \eta_{\text{Dual}} > \eta_{\text{Diesel}}$$

- c. **Same Peak Pressure, Peak Temperature and Heat Rejection :**

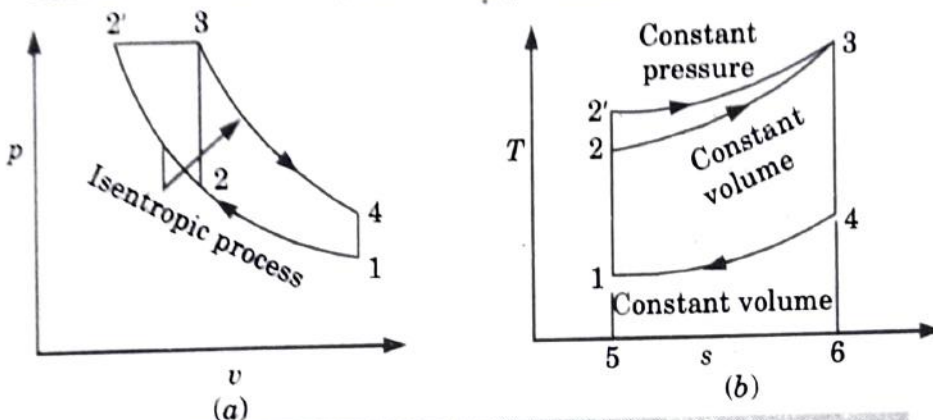


Fig. 1.19.3. Same peak pressure, temperature and heat rejection.

1. In Fig. 1.19.3, Otto and diesel cycle are shown on $p-v$ and $T-s$ diagram as :

Otto cycle : 1-2-3-4

Diesel cycle : 1-2'-3-4

2. Efficiency of Otto and diesel cycle is given as,

$$\eta_{\text{Otto}} = 1 - \frac{Q_R}{Q_S}$$

$$\eta_{\text{Diesel}} = 1 - \frac{Q_R}{Q'_S}$$

3. From the $T-s$ diagram, it is clear that

$$Q'_S > Q_S$$

(Heat supplied)_{Diesel} > (Heat supplied)_{Otto}

4. So, diesel cycle efficiency is greater than Otto cycle.
5. From above analysis, we can conclude that

$$\eta_{\text{Diesel}} > \eta_{\text{Dual}} > \eta_{\text{Otto}}$$

d. Same Maximum Pressure and Heat Input :

1. In Fig. 1.19.4, Otto and Diesel cycle are shown on $p-v$ and $T-s$ diagram as :

Otto cycle : 1-2-3-4-1

Diesel cycle : 1-2'-3'-4'-1

2. From Fig. 1.19.4(b), it is clear that
 $(\text{Heat rejection})_{\text{Otto}} > (\text{Heat rejection})_{\text{Diesel}}$
3. So, diesel cycle will be more efficient, but one should make note that cycle having more efficiency have more expansion. So, diesel cycle efficiency is more and Otto cycle efficiency is least.
4. From this analysis, we can conclude that

$$\eta_{\text{Diesel}} > \eta_{\text{Dual}} > \eta_{\text{Otto}}$$

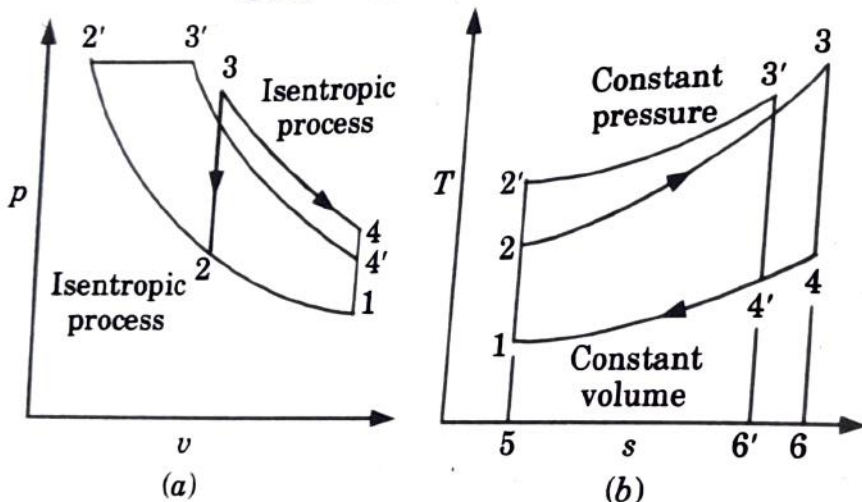


Fig. 1.19.4. Same maximum pressure and heat input.

VERY IMPORTANT QUESTIONS

Following questions are very important. These questions may be asked in your SESSIONALS as well as UNIVERSITY EXAMINATION.

Q. 1. Write short note on following :

- Solid Fuels,
- Liquid Fuels, and
- Gaseous Fuels.

Refer Q. 1.1, Unit-1.

Q. 2. Explain the working procedure of Orsat apparatus for exhaust gas analysis.

2

UNIT

Vapour Power Cycles

CONTENTS

- Part-1** : Vapour Power Cycles, Rankine 2-2A to 2-19A
Cycle with Superheat, Reheat and
Regeneration, Energy Analysis,
Rankine Cycle, Effect of Pressure
and Temperature on Rankine Cycle,
Reheat Cycle, Regenerative Cycle
- Part-2** : Feed Water Heaters 2-19A to 2-20A
- Part-3** : Binary Vapour Cycle 2-20A to 2-24A
- Part-4** : Combined Cycles, Cogeneration 2-24A to 2-27A
- Part-5** : Combustion Analysis 2-27A to 2-28A
- Part-6** : Heating Values, Air Requirement, 2-28A to 2-31A
Air/Fuel Ratio
- Part-7** : Standard Heat of Reaction 2-32A to 2-34A
and Effect of Temperature on
Standard Heat of Reaction, Heat
of Formation, Adiabatic Flame
Temperature

PART-1

Vapour Power Cycles, Rankine Cycle with Superheat, Reheat and Regeneration, Exergy Analysis, Rankine Cycle, Effect of Pressure and Temperature on Rankine Cycle, Reheat Cycle, Regenerative Cycle.

CONCEPT OUTLINE

Vapour Power Cycle : Thermodynamic cycles whose working fluid is vapour or steam are known as vapour power cycles. These include Carnot cycle, Rankine cycle etc.

Exergy : It is a measure of the maximum useful work that can be done by a system interacting with an environment which is at a constant pressure and temperature.

Exergy Analysis : It is powerful tool that allows evaluating and analyzing processes by identifying their imperfection due to thermodynamic irreversibilities.

Questions-Answers**Long Answer Type and Medium Answer Type Questions**

Que 2.1. Explain the Carnot vapour power cycle with T - s diagram. Also find out the efficiency of Carnot cycle.

Answer

A. Carnot Cycle :

1. It is an ideal cycle having highest thermodynamic efficiency. Carnot cycle is shown in Fig. 2.1.1.

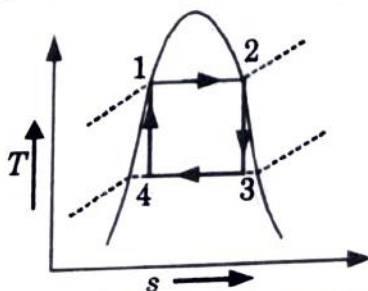


Fig. 2.1.1. Carnot vapour power cycle.

2. Various processes of Carnot cycle are as follows :
 - a. **Process 1-2 :** It is reversible isothermal heat addition process in the boiler.

- b. **Process 2-3** : It is reversible adiabatic expansion process in steam turbine.
 c. **Process 3-4** : It is reversible isothermal heat rejection process in the condenser.
 d. **Process 4-1** : It is reversible adiabatic compression process or pumping process in feed water pump.

B. Efficiency :

1. Net work = Turbine work - Pump work

For unit mass flow,

$$W = (h_2 - h_3) - (h_1 - h_4)$$

2. Heat added in process 1-2,

$$Q_{1-2} = h_2 - h_1$$

3. Thermal efficiency = $\frac{\text{Net work}}{\text{Heat added}}$

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

$$= 1 - \frac{h_3 - h_4}{h_2 - h_1}$$

4. Heat rejected in process 3-4,

$$Q_{3-4} = h_3 - h_4$$

So,

$$\eta_{\text{Carnot}} = 1 - \frac{Q_{3-4}}{Q_{1-2}}$$

5. Heat added or rejected can also be expressed in terms of temperature and entropy, so

$$Q_{3-4} = T_3 (s_3 - s_4)$$

and

$$Q_{1-2} = T_1 (s_2 - s_1)$$

$$\eta_{\text{Carnot}} = 1 - \frac{T_3 (s_3 - s_4)}{T_1 (s_2 - s_1)}$$

6. As we know, $s_1 = s_4$ and $s_2 = s_3$

So,

$$s_3 - s_4 = s_2 - s_1$$

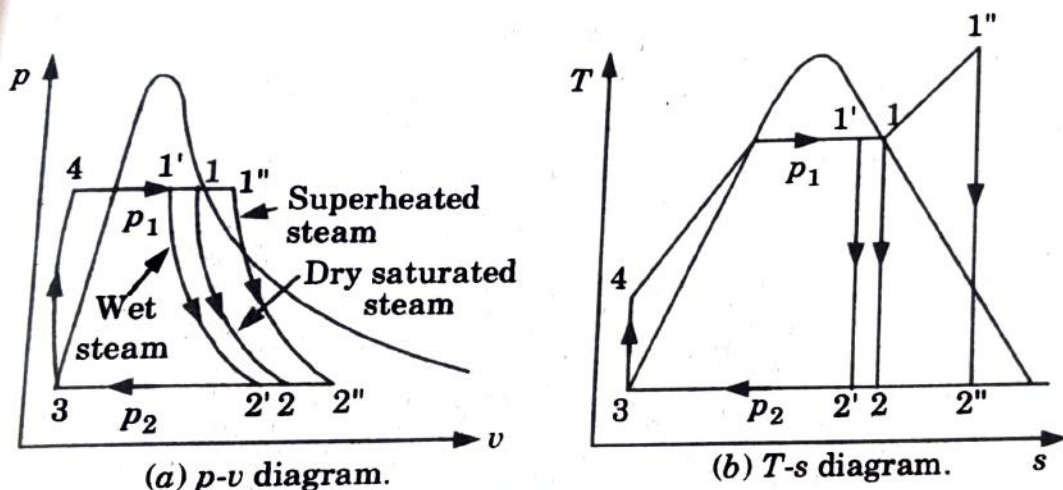
$$\eta_{\text{Carnot}} = 1 - \frac{T_3}{T_1}$$

Que 2.2. Draw $p-v$ and $T-s$ diagram for a Rankine cycle. Derive expression for work done and efficiency of cycle. Explain how it is different from modified Rankine cycle ?

AKTU 2014-15, Marks 10

Answer**A. Rankine Cycle :**

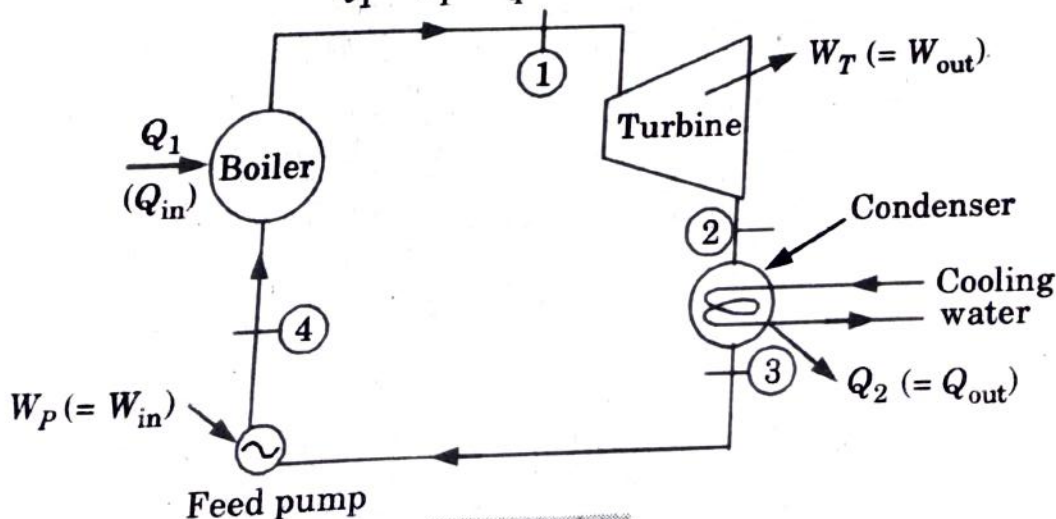
1. It is a thermodynamic cycle derived from Carnot vapour power cycle for overcoming its limitations.
2. In Fig. 2.2.1(a), Rankine cycle is shown on $p-v$, and $T-s$ diagram. It consists of the following processes :
 - a. **Process (1-2) :** It is reversible adiabatic expansion process in turbine.
 - b. **Process (2-3) :** It is constant pressure heat rejection process in condenser.
 - c. **Process (3-4) :** It is reversible adiabatic pumping process in feed water pump.
 - d. **Process (4-1) :** It is constant pressure heat addition process in the boiler.

**Fig. 2.2.1.****B. Work Done :**

1. Rankine cycle is theoretical cycle for steam power plant.
2. Steady flow energy equation for boiler,

$$h_4 + Q_1 = h_1$$

$$Q_1 = h_1 - h_4$$

**Fig. 2.2.2.**

3. Steady flow energy equation for turbine,

$$h_1 = W_T + h_2$$

$$W_T = h_1 - h_2$$

4. Steady flow energy equation for condenser,

$$h_2 = Q_2 + h_3$$

$$Q_2 = h_2 - h_3$$

5. Steady flow energy equation for pump,

$$h_3 + W_P = h_4$$

$$W_P = h_4 - h_3$$

C. Efficiency:

1. Efficiency,
$$\eta = \frac{W_{\text{net}}}{Q_1} = \frac{W_T - W_P}{Q_1} = \frac{(h_1 - h_2) - (h_4 - h_3)}{h_1 - h_4}$$

2. Now for adiabatic compression,

$$Tds = dh - vdp$$

Since, $ds = 0$

$$dh = vdp$$

$$\int_3^4 dh = \int_3^4 vdp$$

$$h_4 - h_3 = v_3 (p_4 - p_3) = W_P$$

3. W_P (pump work) is usually small in comparison to W_T (turbine work). So we neglect this and efficiency expression becomes,

$$\eta = \frac{h_1 - h_2}{h_1 - h_4}$$

D. Difference between Rankine and Modified Rankine Cycle :

S. No.	Rankine Cycle	Modified Rankine Cycle
1.	Lower thermal efficiency.	Higher thermal efficiency.
2.	More thermal stresses set-up in the boiler.	Less thermal stresses set-up in the boiler.
3.	Simple plant design.	Complicated plant design.
4.	Large size condenser is required.	Small size condenser is required.
5.	Less maintenance is required.	More maintenance is required.
6.	For a given power, a small capacity boiler is required.	For a given power, a large capacity boiler is required.

Que 2.3. Explain Rankine cycle with superheated steam.

Answer

1. Fig. 2.3.1 shows Rankine cycle with superheated steam.
2. If the heating of the working fluid is continued beyond the dry saturation point, i.e., well into the superheat regime before feeding it to the turbine (Fig. 2.3.1.) i.e., state 1' instead of state 1, the amount of heat added increases.
3. This brings about an increase in the work output ($\Delta W_{\text{output}} = \text{area } 1-1'-2'-2$). So superheating results in higher cycle efficiency.

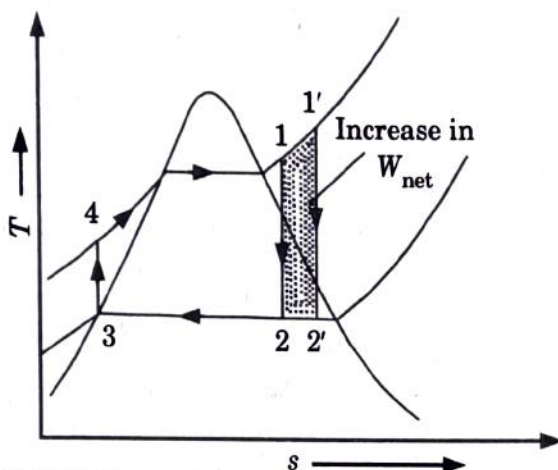


Fig. 2.3.1. T - s diagram of a Rankine cycle operating with a superheated steam.

Que 2.4. Explain reheat Rankine cycle with the help of neat schematic diagram and T - s chart.

Answer

1. In reheating, all the steam after partial expansion in the turbine is brought back to the boiler, reheated by combustion gases and then feed back to turbine for further expansion.
2. Here steam generated in boiler is supplied to high pressure steam turbine at state 2 and is expanded upto state 3.
3. This steam is sent to boiler for being reheated so that its temperature gets increased, normally this temperature after reheating may be equal to temperature at inlet of high pressure steam turbine.
4. Steam after reheating is supplied to subsequent turbine at state 4, say to low pressure steam turbine.
5. Steam is now expanded upto the exhaust pressure say state 5.
6. Expanded steam is subsequently sent to condenser and condensate at state 6 is pumped back to boiler employing feed pump at state 1.

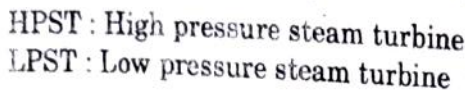


Fig. 2.4.1. Reheat cycle.

- $$\text{Heat supplied} = (h_1 - h_{f4}) + (h_3 - h_2)$$

$$\text{Heat rejected} = h_4 - h_{f4}$$

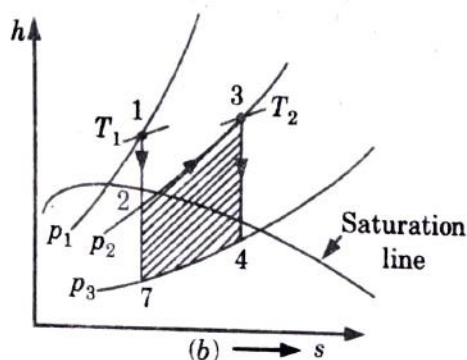


Fig. 2.4.2. Ideal reheating process on (a) T - s and (b) h - s charts.

9. Work done by the turbine = Heat supplied – Heat rejected

$$= (h_1 - h_{f4}) + (h_3 - h_2) - (h_4 - h_{f4})$$

$$= (h_1 - h_2) + (h_3 - h_4)$$

10. Thermal efficiency of reheat cycle,

$$\eta_{\text{Thermal}} = \frac{\text{Work done by turbine}}{\text{Heat supplied}}$$

$$= \frac{(h_1 - h_2) + (h_3 - h_4)}{(h_1 - h_{f4}) + (h_3 - h_2)}$$

Que 2.5. Enumerate effect of pressure and temperature on Rankine cycle.

AKTU 2014-15, Marks 05

Answer

A. Effect of Pressure of Steam at Inlet to Turbine :

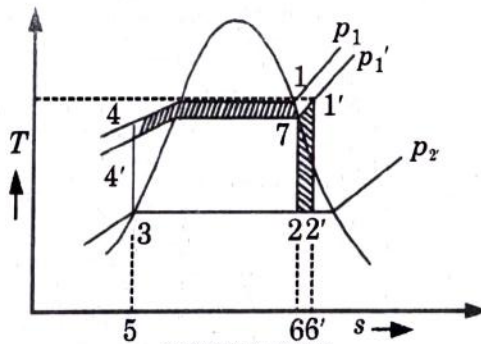


Fig. 2.5.1.

- For same back pressure and steam inlet temperature, the increase in steam inlet pressure from p_1 to p_1' is accompanied by the reduction in net heat added as shown by area $A_{1'2'271}$ and increase in net heat added by the amount shown by area $A_{4'4174'}$.

Generally, $A_{1'2'271} = A_{4'4174'}$

(Heat rejected)_{cycle 1234} < (Heat rejected)_{cycle 1'2'3'4'}

$$\eta_{\text{cycle}} = 1 - \frac{\text{Heat rejected}}{\text{Heat added}}$$

- Increase in steam pressure at inlet to steam turbine is accompanied by increase in cycle thermal efficiency.

B. Effect of Temperature of Steam at Inlet to Turbine :

- From the given Fig. 2.5.2, it is clear that increase in inlet temperature from T_1 to T_1' (Let $T_1 < T_1'$) increases net work and heat addition.

Net increased work = Area $A_{11'2'21}$

Net increased heat addition = Area $A_{11'6'61}$

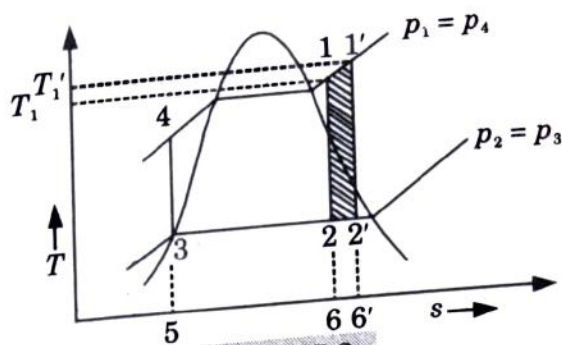


Fig. 2.5.2.

2. So, it is clear that increase in steam temperature from T_1 to T_1' increases mean temperature of heat addition, which increases the thermal efficiency.

C. Effect of Pressure at the End of Expansion :

1. With same maximum pressure and temperature, the reduction in back pressure from p_2 to p_2' causes increment in net work and in heat addition.

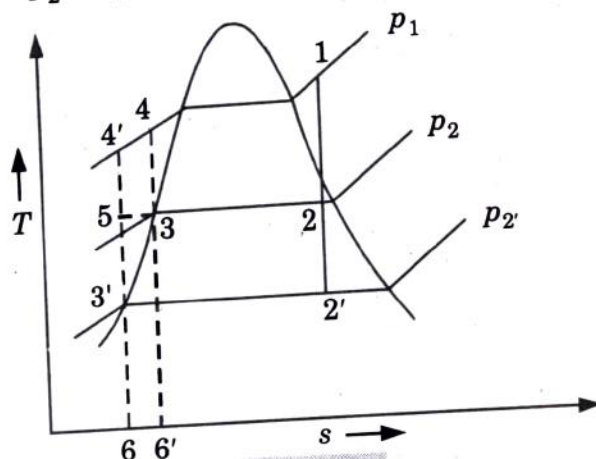


Fig. 2.5.3.

From Fig. 2.5.3, it is clear that

Increment in net work = Area $4'4322'3'54'$

Increment in heat addition = Area $4'466'4'$

2. So, the thermal efficiency of cycle increases by lowering back pressure as increase in heat addition is more than increase in heat rejection.

Que 2.6. Explain regeneration cycle with the help of neat diagram. Derive the expression for efficiency.

Answer

A. Regenerative Cycle :

1. In regenerative cycle, the feed water entering the boiler is heated by steam extracted from intermediate stages of turbine.

Here, turbine is double extracting and boiler is equipped with a superheater.

The flow diagram of regenerative cycle is shown in Fig. 2.6.2 on T - s diagram.

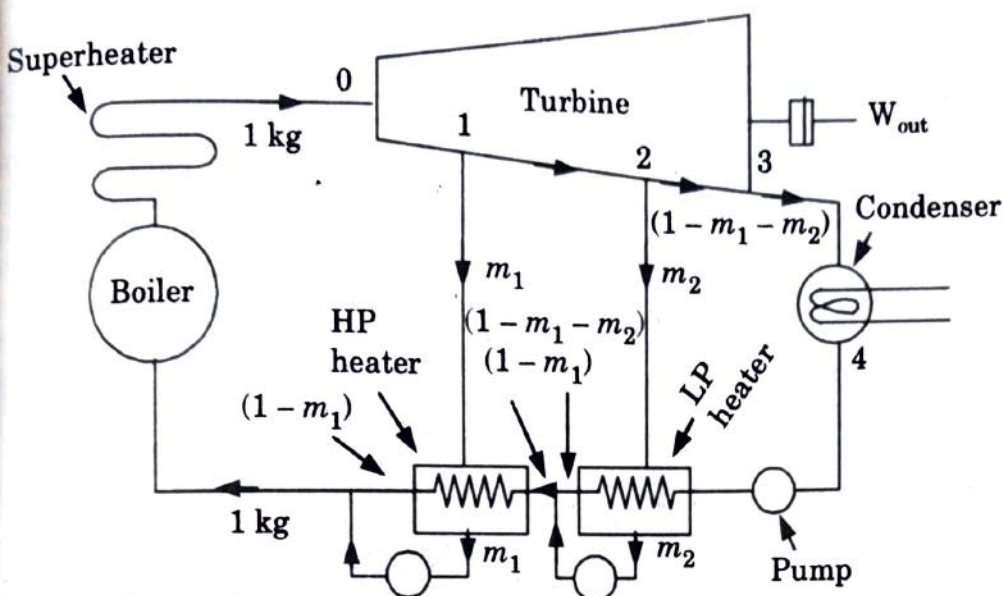


Fig. 2.6.1. Regenerative cycle.

Efficiency :

Let,

m_1 = Mass of high pressure steam per kg of steam flow,

m_2 = Mass of low pressure steam per kg extracted of steam flow, and

$(1 - m_1 - m_2)$ = Mass of steam entering condenser per kg of steam flow.

Heat balance equation for HP heater,

$$m_1(h_1 - h_{f5}) = (1 - m_1)(h_{f6} - h_{f5})$$

$$m_1[(h_1 - h_{f6}) + (h_{f6} - h_{f5})] = (h_{f6} - h_{f5})$$

$$m_1 = \frac{(h_{f6} - h_{f5})}{(h_1 - h_{f5})}$$

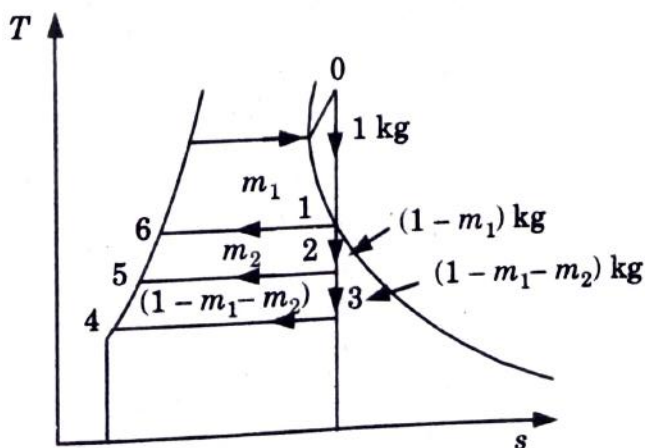


Fig. 2.6.2. T - s diagram of regeneration cycle.

- Here, turbine is double extracting and boiler is equipped with a superheater.
- The flow diagram of regenerative cycle is shown in Fig. 2.6.2 on T - s diagram.

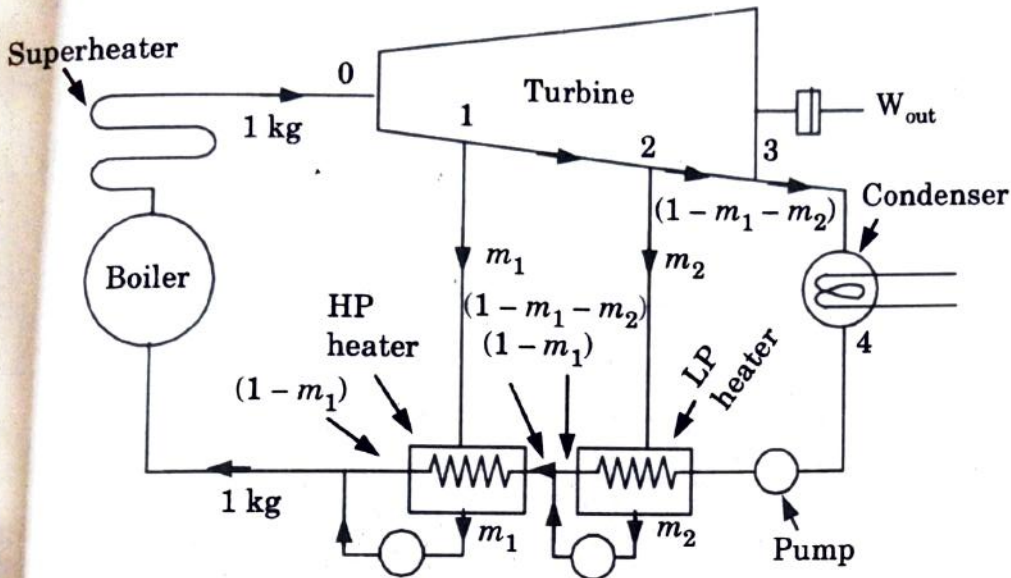


Fig. 2.6.1. Regenerative cycle.

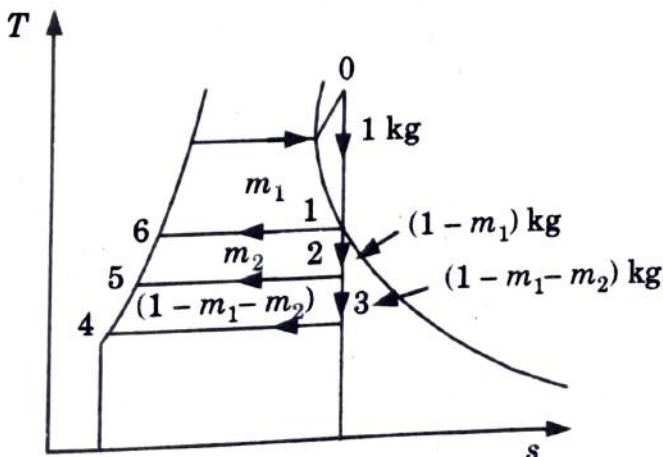
B. Efficiency:

- Let,
 - m_1 = Mass of high pressure steam per kg of steam flow,
 - m_2 = Mass of low pressure steam per kg extracted of steam flow, and
 - $(1 - m_1 - m_2)$ = Mass of steam entering condenser per kg of steam flow.
- Heat balance equation for HP heater,

$$m_1(h_1 - h_{f5}) = (1 - m_1)(h_{f6} - h_{f5})$$

$$m_1[(h_1 - h_{f6}) + (h_{f6} - h_{f5})] = (h_{f6} - h_{f5})$$

$$m_1 = \frac{(h_{f6} - h_{f5})}{(h_1 - h_{f5})}$$

Fig. 2.6.2. T - s diagram of regeneration cycle.

3. Heat balance equation for LP heater,

$$m_2(h_2 - h_{f5}) = (1 - m_1 - m_2)(h_{f5} - h_{f3})$$

$$m_2[(h_2 - h_{f5}) + (h_{f5} - h_{f3})] = (1 - m_1)(h_{f5} - h_{f3})$$

$$m_2 = \frac{(1 - m_1)(h_{f5} - h_{f3})}{(h_2 - h_{f3})}$$

4. Heat supplied externally in the cycle $= h_0 - h_{f6}$
 5. Isentropic work done $= m_1(h_0 - h_1) + m_2(h_0 - h_2) + (1 - m_1 - m_2)(h_0 - h_3)$
 6. The thermal efficiency of regenerative cycle is,

$$\eta_{\text{thermal}} = \frac{\text{Work done}}{\text{Heat supplied}}$$

$$= \frac{m_1(h_0 - h_1) + m_2(h_0 - h_2) + (1 - m_1 - m_2)(h_0 - h_3)}{(h_0 - h_{f6})}$$

Que 2.7. A simple Rankine cycle works between pressures 28 bar and 0.06 bar, the initial condition of steam being dry saturated. Calculate the dryness fraction, cycle efficiency, work ratio and specific steam consumption.

AKTU 2017-18, Marks 10

Answer

Given : $p_1 = 28 \text{ bar}$, $p_2 = 0.06 \text{ bar}$

To Find : i. Dryness fraction.

ii. Cycle efficiency.

iii. Work ratio.

iv. Specific steam consumption.

1. From steam table,

At 28 bar, $h_1 = 2802 \text{ kJ/kg}$, $s_1 = 6.2104 \text{ kJ/kg K}$

At 0.06 bar, $h_{f2} = h_{f3} = 151.15 \text{ kJ/kg}$, $h_{fg2} = 2415.9 \text{ kJ/kg}$

$s_{f2} = 0.521 \text{ kJ/kg K}$, $s_{fg2} = 7.809 \text{ kJ/kg K}$

$v_{f3} = 0.001 \text{ m}^3/\text{kg}$

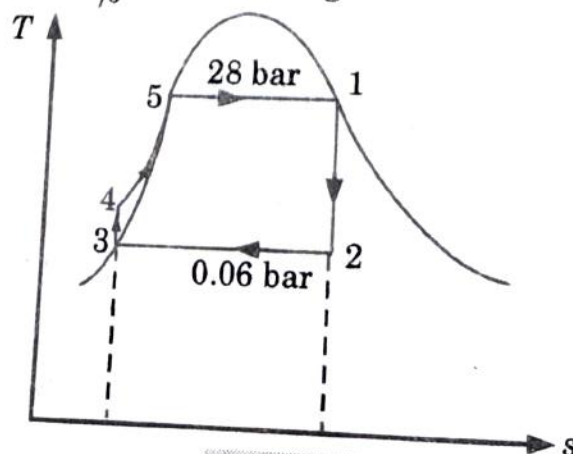


Fig. 2.7.1.

2. Considering turbine process 1-2, we have

$$s_1 = s_2$$

$$6.2104 = s_{f2} + x_2 s_{fg2} = 0.521 + x_2 \times 7.809$$

$$\therefore x_2 = \frac{6.2104 - 0.521}{7.809} = 0.728$$

3. Enthalpy at point 2, $h_2 = h_{f2} + x_2 h_{fg2}$
 $= 151.5 + 0.728 \times 2415.9 = 1910.27 \text{ kJ/kg}$

4. Turbine work, $W_T = h_1 - h_2 = 2802 - 1910.27 = 891.73 \text{ kJ/kg}$

5. Pump work, $W_P = h_{f4} - h_{f3} = v_{f3} (p_1 - p_2)$
 $= \frac{0.001(28 - 0.06) \times 10^5}{1000} = 2.79 \text{ kJ/kg}$

$$\therefore h_{f4} = h_{f3} + W_P = 151.5 + 2.79 = 154.29 \text{ kJ/kg}$$

6. Net work, $W_{\text{net}} = W_T - W_P$
 $= 891.73 - 2.79 = 888.94 \text{ kJ/kg}$

7. Cycle efficiency, $\eta = \frac{W_{\text{net}}}{Q_1} = \frac{888.94}{h_1 - h_{f4}}$
 $= \frac{888.94}{2802 - 154.29} = 0.3357 \text{ or } 33.57 \%$

8. Work ratio = $\frac{W_{\text{net}}}{W_T} = \frac{888.94}{891.73} = 0.997$

9. Specific steam consumption = $\frac{3600}{W_{\text{net}}} = \frac{3600}{888.94} = 4.049 \text{ kg/kW h}$

Que 2.8. A steam engine working on Rankine cycle operates between 1.96 MPa, 250 °C and 13.7 kPa. If engine consumes steam at the rate of 0.086 kg per second, determine Rankine cycle efficiency, neglecting pump work. Also, find Rankine cycle efficiency considering pump work.

AKTU 2018-19, Marks 10

Answer

Given : $T_1 = 250^\circ\text{C}$, $p_1 = 1.96 \text{ MPa} = 19.6 \text{ bar}$
 $p_2 = 13.7 \text{ kPa} = 0.13 \text{ bar}$, $m = 0.086 \text{ kg/s}$

To Find : i. Rankine efficiency neglecting pump work.
 ii. Rankine efficiency considering pump work.

- From steam table, at 19.6 bar and 250 °C,
 $h_1 = 2902.5 \text{ kJ/kg}$, $s_1 = 6.545 \text{ kJ/kgK}$, $v_{f1} = 0.111 \text{ m}^3/\text{kg}$
- From steam table, at 0.13 bar,
 $h_{f2} = 213.7 \text{ kJ/kg}$, $h_{fg2} = 2380.2 \text{ kJ/kg}$, $s_{f2} = 0.717 \text{ kJ/kgK}$

$$s_{fg2} = 7.341 \text{ kJ/kgK}, v_{f2} = 0.001013 \text{ m}^3/\text{kg}$$

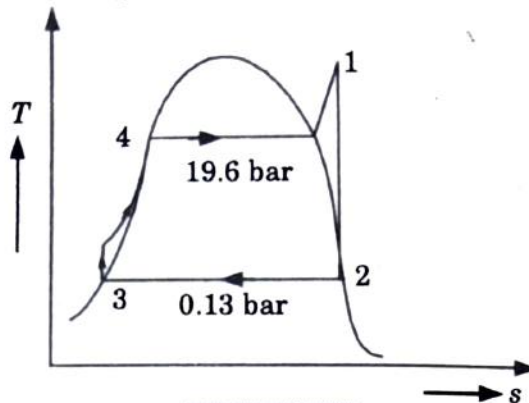


Fig. 2.8.1.

3. Since process 1 and 2 are isentropic,

So

$$s_1 = s_2$$

$$6.545 = 0.717 + x_2 7.341$$

$$(\because s_2 = s_{f2} + x_2 s_{fg2})$$

$$x_2 = 0.7938$$

4. Enthalpy at 2,

$$\begin{aligned} h_2 &= h_{f2} + x_2 h_{fg2} \\ &= 213.7 + 0.7938 \times 2380.2 \\ &= 2103.10 \text{ kJ/kg} \end{aligned}$$

5. Turbine work, $W_T = m(h_1 - h_2)$

$$\begin{aligned} &= 0.086 (2902.5 - 2103.10) \\ &= 68.74 \text{ kJ/s} \end{aligned}$$

6. Pump work,

$$\begin{aligned} W_P &= m v_{f2} (p_1 - p_2) \times 10^2 \\ &= 0.086 \times 0.001013 (19.6 - 0.13) \times 10^2 \\ &= 0.1696 \text{ kJ/s} \end{aligned}$$

7. Heat supplied,

$$\begin{aligned} Q_1 &= m(h_1 - h_{f4}) \\ &= 0.086 (2902.5 - 213.7) \\ &= 231.23 \text{ kJ/s} \end{aligned}$$

$$(\because h_{f4} = h_{f2})$$

8. Rankine efficiency neglecting pump work,

$$\begin{aligned} \eta &= \frac{W_{\text{net}}}{\text{Heat supplied}} = \frac{W_T}{Q_1} = \frac{68.74}{231.23} \\ &= 0.297 = 29.7 \% \end{aligned}$$

9. Heat supplied considering pump work,

$$\begin{aligned} Q_1 &= m(h_1 - h_{f4}) & (\because h_{f4} = h_{f2} + W_{\text{pump}}) \\ h_{f4} &= 213.7 + 0.1692 \\ &= 213.86 \\ Q_1 &= 0.086 (2902.5 - 213.86) \\ &= 231.22 \text{ kJ/s} \end{aligned}$$

10. Rankine efficiency considering pump work,

$$\begin{aligned} \eta &= \frac{W_{\text{net}}}{\text{Heat supplied}} = \frac{W_T - W_P}{Q_1} \\ &= \frac{68.74 - 0.1696}{231.22} = 0.2965 = 29.6 \% \end{aligned}$$

Que 2.9. Steam is the working fluid in an ideal Rankine cycle. Saturated vapour enters the turbine at 8.0 MPa and saturated liquid exits the condenser at a pressure of 0.008 MPa. The net power output of the cycle is 100 MW. Determine for the cycle (i) The thermal efficiency, (ii) the back work ratio, (iii) the mass flow rate of the steam, in kg/h.

AKTU 2016-17, Marks 15

Answer

Given : $p_1 = 8 \text{ MPa} = 80 \text{ bar}$, $p_2 = 0.008 \text{ MPa} = 0.08 \text{ bar}$,
Power output = 100 MW

1. From steam table,

At 80 bar, $h_1 = 2759.9 \text{ kJ/kg}$, $s_1 = 5.7471 \text{ kJ/kgK}$

At 0.08 bar, $h_3 = h_{f3} = 173.9 \text{ kJ/kg}$, $h_{fg2} = 2403.1 \text{ kJ/kg}$

$s_{f2} = 0.593 \text{ kJ/kgK}$, $s_{fg2} = 7.636 \text{ kJ/kgK}$

$v_3 = v_f = 0.001008 \text{ m}^3/\text{kg}$

2. Considering process 1-2, we have

$$s_1 = s_2$$

$$5.7471 = s_{f2} + x_2 s_{fg2}$$

$$5.7471 = 0.593 + x_2 7.636$$

$$x_2 = \frac{5.7471 - 0.593}{7.636} = 0.675$$

$$\therefore h_2 = h_{f2} + x_2 h_{fg2} \quad [\because h_{f2} = h_{f3}]$$

$$= 173.9 + 0.675 \times 2403.1 = 1795.925 \text{ kJ/kg}$$

3. Turbine work,

$$W_T = h_1 - h_2$$

$$= 2759.9 - 1795.925 = 963.98 \text{ kJ/kg}$$

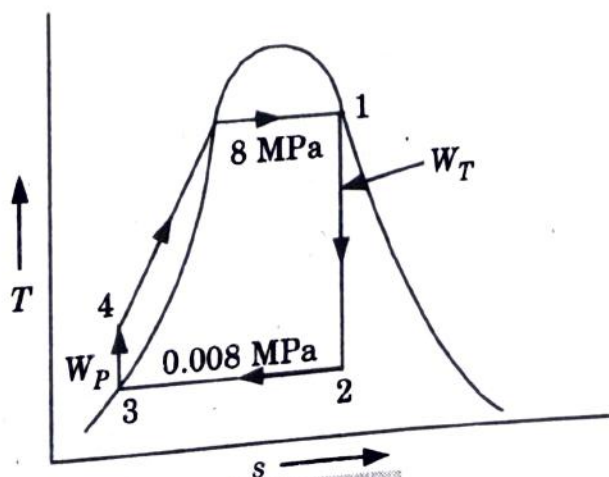


Fig. 2.9.1.

4. Pump work, $W_P = h_{f4} - h_{f3} = v_f(p_1 - p_2)$
 $= 0.001008(8 - 0.008) \times 10^3 = 8.0056 \text{ kJ/kg}$
 $h_{f4} = W_P + h_{f3} = 8.0056 + 173.9 = 181.91 \text{ kJ/kg}$
5. Net work $W_{\text{net}} = W_T - W_P$
 $= 963.98 - 8.0056 = 955.97 \text{ kJ/kg}$
6. Heat added, $Q_1 = h_1 - h_{f4}$
 $= 2759.9 - 181.91 = 2577.99 \text{ kJ/kg}$
7. Thermal efficiency, $\eta = \frac{W_{\text{net}}}{Q_1} = \frac{955.97}{2577.99}$
 $\eta = 37.08 \%$
8. Back work ratio, $W_r = \frac{W_P}{W_T} = \frac{8.0056}{963.98} = 0.008304$
9. Mass flow rate of steam,
 $m_s = \frac{\text{Power output}}{W_{\text{net}}} = \frac{100 \times 10^3}{955.97}$
 $= 104.61 \text{ kg/s} = 376580 \text{ kg/hour}$

Que 2.10. A steam power plant running on Rankine cycle has steam entering HP turbine at 20 MPa, 500 °C and leaving LP turbine at 90 % dryness. Considering condenser pressure of 0.005 MPa and reheating occurring up to the temperature of 500 °C. Determine :

- a. The pressure at which steam leaves HP turbine.
- b. The thermal efficiency.

AKTU 2016-17, Marks 10

Answer

Given : $T_2 = 500^\circ\text{C}$, $p_2 = 20 \text{ MPa} = 200 \text{ bar}$, $x_5 = 0.9$, $p_6 = 0.005 \text{ MPa}$

1. Let us assume that the condensate leaves condenser as saturated liquid and the expansion in turbine and pumping processes are isentropic.
2. From steam table,

At 200 bar and 500 °C : $h_2 = 3238.2 \text{ kJ/kg}$, $s_2 = 6.1401 \text{ kJ/kgK}$

At 0.005 bar : $h_{f5} = 137.82 \text{ kJ/kg}$, $h_{fg5} = 2423.7 \text{ kJ/kg}$
 $v_5 = 0.001005 \text{ m}^3/\text{kg}$, $s_{f5} = 0.4764 \text{ kJ/kg}$

$s_{fg5} = 7.9187 \text{ kJ/kg}$

$h_5 = h_{f5} + 0.9 \times h_{fg5}$
 $= 137.82 + 0.9 \times 2423.7$
 $= 2319.15 \text{ kJ/kg}$

$s_5 = s_{f5} + 0.9 \times s_{fg5}$
 $= 0.4764 + 0.9 \times 7.9187$

$$= 7.6032 \text{ kJ/kgK}$$

3. It is given that temperature at state 4 is 500°C and due to isentropic process $s_4 = s_5 = 7.6032 \text{ kJ/kgK}$. The state 4 can be conveniently located on Mollier chart by the intersection of 500°C constant temperature line and entropy value of 7.6032 kJ/kgK and the pressure and enthalpy will be obtained but these shall be approximate values.
4. The state 4 can also be located by interpolation using steam table.

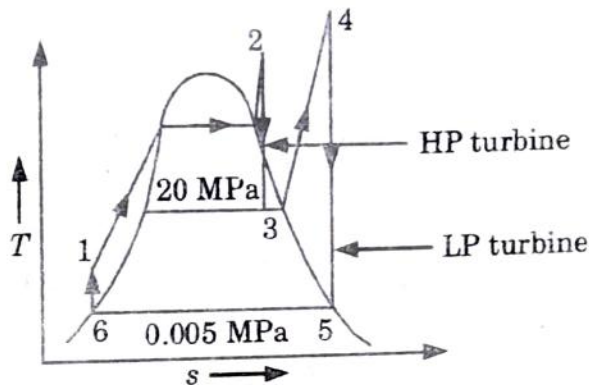


Fig. 2.10.1.

5. The entropy value of 7.6032 kJ/kgK lies between the superheated steam states given under, $p = 1.20 \text{ MPa}$,
 $s_{\text{at } 1.20 \text{ MPa and } 500^\circ\text{C}} = 7.6759 \text{ kJ/kgK}$
 $p = 1.40 \text{ MPa}$, $s_{\text{at } 1.40 \text{ MPa and } 500^\circ\text{C}} = 7.6027 \text{ kJ/kgK}$
6. By interpolation state 4 lies at pressure,

$$= 1.20 + \frac{(1.40 - 1.20)}{(7.6027 - 7.6759)}(7.6032 - 7.6759)$$

$$= 1.399 \text{ MPa} \approx 1.4 \text{ MPa}$$

Thus, steam leaves HP turbine at 1.4 MPa .

7. At 14 bar :
 $s_{f3} = 2.2842 \text{ kJ/kgK}$, $s_{fg3} = 4.185 \text{ kJ/kgK}$
 $s_{g3} = 6.4651 \text{ kJ/kgK}$
 $h_{f3} = 830.3 \text{ kJ/kgK}$
 $h_{fg3} = 1959.7 \text{ kJ/kgK}$

8. Enthalpy at state 4, $h_4 = 3474.1 \text{ kJ/kg}$
 For process 2-3, $s_2 = s_3 = 6.1401 \text{ kJ/kgK}$. The state 3 thus lies in wet region as $s_3 < s_g$.
 Let dryness fraction at state 3 be x_3 .

$$s_3 = s_{f3} + x_3 s_{fg3}$$

$$6.1401 = 2.2842 + x_3 4.185$$

$$x_3 = 0.9214$$

$$h_3 = h_{f3} + x_3 h_{fg3}$$

$$= 830.3 + 0.9214 \times 1959.7 = 2635.97 \text{ kJ/kg}$$

9. Enthalpy at 1, $h_1 = h_6 + v_6(p_1 - p_6)$ [$\because h_6 = h_{f5}$ and $v_6 = v_5$]

$$= 137.82 + 0.001005 (20 - 0.005) \times 10^3$$

$$h_1 = 157.91 \text{ kJ/Kg}$$

Net work per kg of steam = $(h_2 - h_3) + (h_4 - h_5) - (h_1 - h_{f5})$

$$= (3238.2 - 2635.97) + (3474.1 - 2319.15) - (157.91 - 137.82)$$

$$= 1737.09 \text{ kJ/kg}$$

Heat added per kg of steam,

$$(h_2 - h_1) = (3238.2 - 157.91) = 3080.29 \text{ kJ/kg}$$

11. Thermal efficiency = $\frac{\text{Net work}}{\text{Heat added}} = \frac{1737.09}{3080.29} = 0.5639$ or 56.39 %

Que 2.11. A steam power plant operates on the regenerative cycle.

Steam from boiler at 30 bar and 400 °C is expanded in a turbine. A part of the steam is bled at 2 bar pressure into the feed water heater and the remainder is condensed at 0.07 bar. Neglecting pump work, determine the work done per kg of steam and the efficiency of the cycle.

AKTU 2015-16, Marks 10

Answer

Given : $p_1 = 30 \text{ bar}$, $T_1 = 400 \text{ °C}$, $p_2 = 2 \text{ bar}$ and $p_3 = 0.07 \text{ bar}$

To Find :

- Work done per kg of steam.
- Efficiency of cycle.

1. From steam table :

i. At 30 bar and 400 °C :

$$h_1 = 3230.9 \text{ kJ/kg}, s_1 = 6.921 \text{ kJ/kgK and}$$

$$s_1 = s_2 = s_3$$

ii. At 2 bar :

$$h_f = 504 \text{ kJ/kg}, s_f = 1.530 \text{ kJ/kgK},$$

$$s_g = 7.127 \text{ kJ/kgK}, h_{fg} = 2201.6 \text{ kJ/kg}$$

$$s_{fg} = 5.597 \text{ kJ/kgK}$$

Since, $s_2 < s_g$. So point 2 must lie in wet region.

iii. At 0.07 bar :

$$s_f = 0.559 \text{ kJ/kgK}, s_{fg} = 7.719 \text{ kJ/kgK},$$

$$h_f = 163.4 \text{ kJ/kg}, h_{fg} = 2409.2 \text{ kJ/kg}$$

$$v_f = 0.001007 \text{ m}^3/\text{kg}$$

2. Since,

$$s_1 = s_3$$

$$6.921 = s_{f3} + x_3 s_{fg3}$$

$$6.921 = 0.559 + x_3 \times 7.719$$

$$x_3 = 0.824$$

$\therefore$

$$h_3 = h_{f3} + x_3 h_{fg3}$$

$$= 163.4 + 0.824 \times 2409.2$$

$$= 2148.58 \text{ kJ/kg}$$

3. Also,

$$s_1 = s_2$$

$$6.921 = s_{f2} + x_2 s_{fg2}$$

$$6.921 = 1.530 + x_2 (5.597)$$

$$x_2 = 0.9631$$

$$h_2 = h_{f2} + x_2 h_{fg2}$$

$$= 504 + 0.9631 \times 2201.6$$

$$= 2624.36 \text{ kJ/kg}$$

$$h_5 = h_{f4} + v_4 (2 - 0.07) \times 10^2$$

$$= 163.4 + 0.001007 \times 1.93 \times 10^2$$

$$= 163.59 \text{ kJ/kg}$$

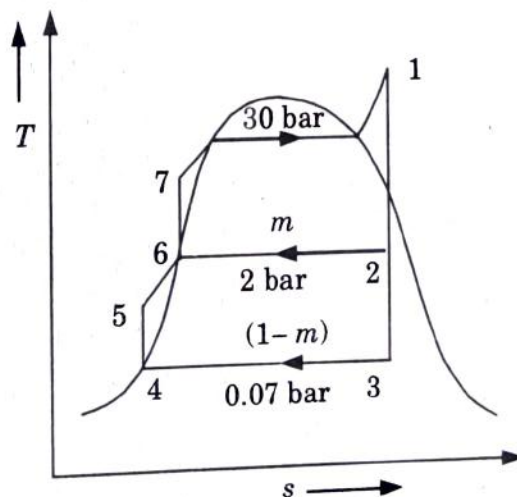


Fig. 2.11.1.

4. Since pump work is neglected,

$$h_{f4} = 163.4 \text{ kJ/kg} = h_5$$

$$h_{f6} = 504 \text{ kJ/kg} = h_7$$

5. By energy balance,

$$m \times h_2 + (1 - m) h_5 = h_7 \times 1$$

$$m \times 2624.36 + (1 - m) 163.59 = 504$$

$$2460.77 m = 340.41$$

$$m = 0.138 \text{ kJ/kg}$$

6. Turbine work,

$$W_T = (h_1 - h_2) + (1 - m) (h_2 - h_3)$$

$$= (3230.9 - 2624.36) + (1 - 0.138)(2624.36 - 2148.58) \\ = 606.54 + 410.12 = 1016.66 \text{ kJ}$$

7. Heat supplied $= h_1 - h_6$
 $= 3230.9 - 504 = 2726.9 \text{ kJ}$

8. Efficiency of cycle,

$$\eta = \frac{\text{Turbine work}}{\text{Heat supplied}} \\ = \frac{1016.66}{2726.9} = 0.3728 \text{ or } 37.28 \%$$

PART-2

Feed Water Heaters.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 2.12. What are the feed water heaters ? Also explain their types.

Answer

A. Feed Water Heaters :

1. Feed water heaters are the devices used for heat exchange between two fluids (*i.e.*, between steam and feed water) either in direct contact or indirect contact.

B. Types of Feed Water Heaters :

a. Open (Direct Contact) Feed Water Heater :

1. In this type of feed water heaters, bled steam and feed water are at same pressure and adiabatic mixing is assumed to take place.

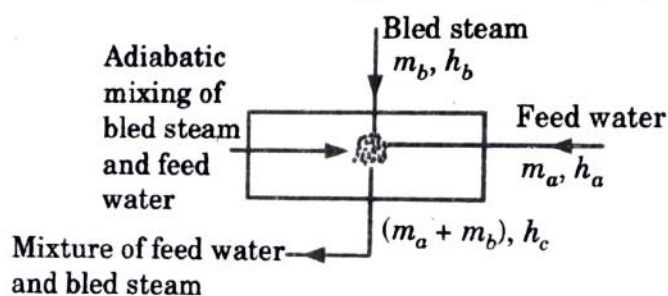


Fig. 2.12.1. Direct contact feed water heater.

2. It is assumed that mixture leaves open feed water heaters as saturated liquid.

3. Using energy balance for direct contact feed water heater

$$m_a h_a + m_b h_b = (m_a + m_b) h_c$$

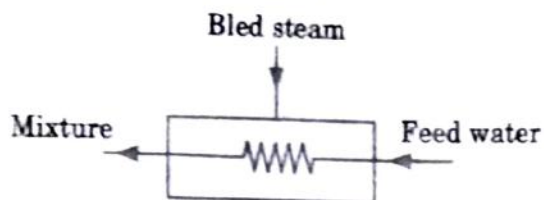


Fig. 2.12.2. Closed feed water heater.

b. Closed (Indirect Contact) Feed Water Heater :

1. In this type of feed water heaters, the bled steam and feed water do not come in direct contact but the heat exchange between two streams occur indirectly through metal interface.
2. In this, two streams (*i.e.*, bled steam and feed water) may be at different pressures.
3. Feed water flows inside the tube and is heated by bled steam from turbine.

Que 2.13. What is bleeding and how does it affects cycle efficiency.

AKTU 2014-15, Marks 05

Answer

1. Bleeding is the process of draining steam from the turbine, at certain points during its expansion and using this steam for heating the feed water supplied to the boiler.
2. Water in feed pipe has temperature lower than the steam.
3. Due to this difference, steam gives its heat to feed water and gets condensed. By this process, efficiency is increased but at the same time the power developed is decreased.

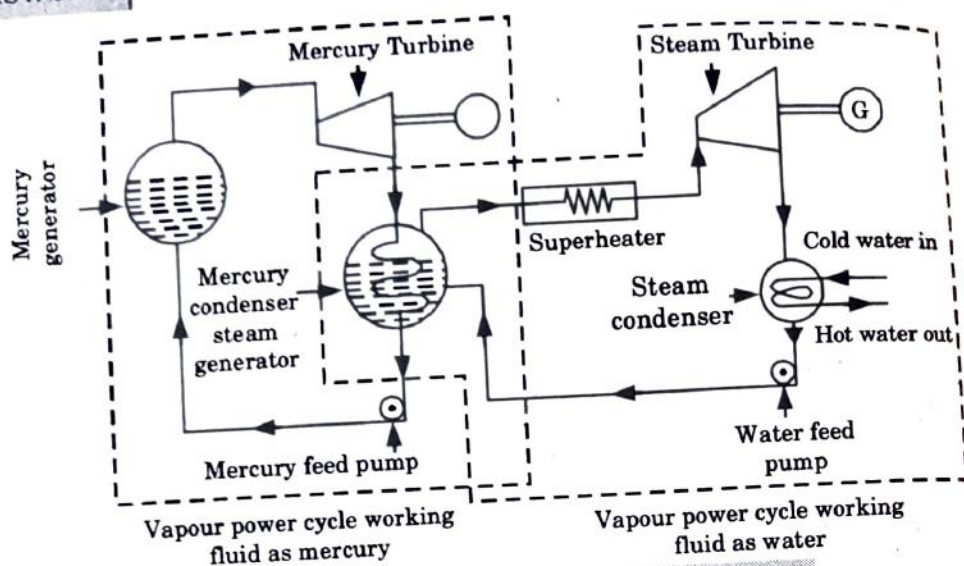
PART-3

Binary Vapour Cycle.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 2.14. Describe binary vapour cycle with neat sketch and *T-s* curve.

Answer**Fig. 2.14.1. Layout of binary vapour cycle.**

- Fig. 2.14.1 is a layout of binary vapour cycle which shows clearly that it is a combination of two vapour power cycles having two different working fluids (water and mercury).
- Mercury vapour is generated in mercury boiler and sent into mercury turbine for its expansion.
- The expanded fluid enters into condenser.
- From condenser, it is again pumped back into the mercury boiler.
- In the mercury condenser (or steam generator) the water extracts the heat from mercury to condense mercury and water converts into the steam.
- This generated steam enters into superheater and becomes superheated steam and enters into steam turbine for expansion and goes into condenser from where it is pumped into steam generator.
- The net work done from cycle = $W_{MT} + W_{ST} - W_P$
- Work done from mercury turbine, $W_{MT} = m_{MT}(h_1 - h_2)$
- Work done from steam turbine,

$$W_{ST} = m_{ST}(h_a - h_b)$$
- Total pump work, $W_P = m_{MT}(h_4 - h_3) + m_{ST}(h_d - h_c)$
- Heat added to the cycle, ...

$$Q_{add} = m_{MT}(h_1 - h_4) + m_{ST}(h_a - h_e)$$
- Binary cycle efficiency,

$$\eta = \frac{W_{net}}{Q_{add}}$$

$$= \frac{m_{MT}(h_1 - h_2) + m_{ST}(h_a - h_b) - m_{MT}(h_4 - h_3) - m_{ST}(h_d - h_c)}{m_{MT}(h_1 - h_4) + m_{ST}(h_a - h_e)}$$

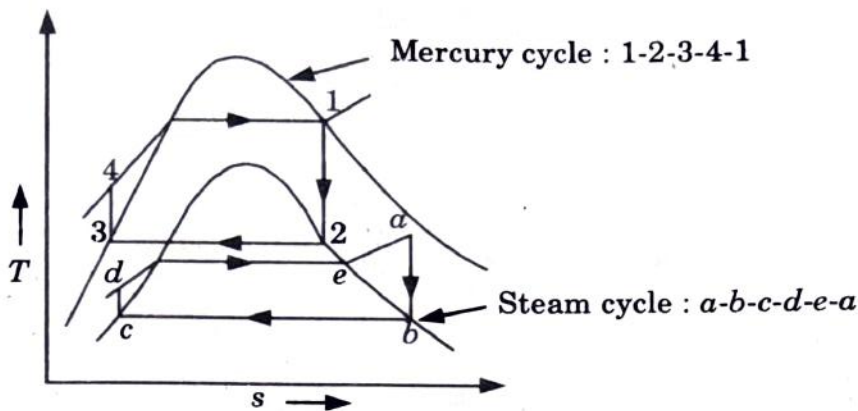


Fig. 2.14.2. Thermodynamic cycle for mercury-steam binary vapour cycle.

Que 2.15. A binary vapour power cycle works on mercury and steam such that dry saturated mercury vapour at 4.5 bar is supplied to mercury turbine and leaves at 0.04 bar. Steam is generated as dry saturated at 15 bar and supplied to steam turbine for being expanded upto condenser pressure of 0.04 bar. Determine thermal efficiency of cycle. For mercury take, h_f at 4.5 bar = 62.93 kJ/kg, h_g at 4.5 bar = 355.98 kJ/kg, v_f at 0.04 bar = 0.0000765 m³/kg, h_f at 0.04 bar = 29.98 kJ/kg, h_g at 0.04 bar = 329.85 kJ/kg, s_g at 4.5 bar = 0.5397 kJ/kgK, s_g at 0.04 bar = 0.6925 kJ/kgK, s_f at 0.04 bar = 0.0808 kJ/kgK.

AKTU 2018-19, Marks 10

Answer

- The binary cycle for given situation is shown in Fig. 2.14.1.
- For mercury cycle, $h_l = 355.98$ kJ/kg
 $s_l = 0.5397$ kJ/kgK
 $= s_m = s_f + x_m s_{fg}$
 or $0.5397 = 0.0808 + x_m (0.6925 - 0.0808)$
 $\therefore x_m = \frac{(0.5397 - 0.0808)}{(0.6925 - 0.0808)} = 0.75$
 $h_m = h_f + x_m h_{fg}$
 $= 29.98 + 0.75 \times (329.85 - 29.98) = 254.88$ kJ/kg
- Work obtained from mercury turbine,
 $(W_T)_{Hg} = h_l - h_m = 355.98 - 254.88 = 101.1$ kJ/kg
- Pump work in mercury cycle,

$$(W_P)_{Hg} = h_{fk} - h_{fn} = v_f(p_2 - p_1)$$

$$= 76.5 \times 10^{-6} \times (4.5 - 0.04) \times 100$$

$$= 0.0341 \text{ kJ/kg}$$

$$W_{net} = 101.1 - 0.0341 \approx 101.1 \text{ kJ/kg}$$

$$Q_1 = h_1 - h_{fk} = 355.98 - 29.98 = 326 \text{ kJ/kg}$$

$$(\because h_{fn} \approx h_{fk})$$

$$\eta_{Hg \text{ cycle}} = \frac{W_{net}}{Q_1} = \frac{101.1}{326} = 0.31 \text{ or } 31 \%$$

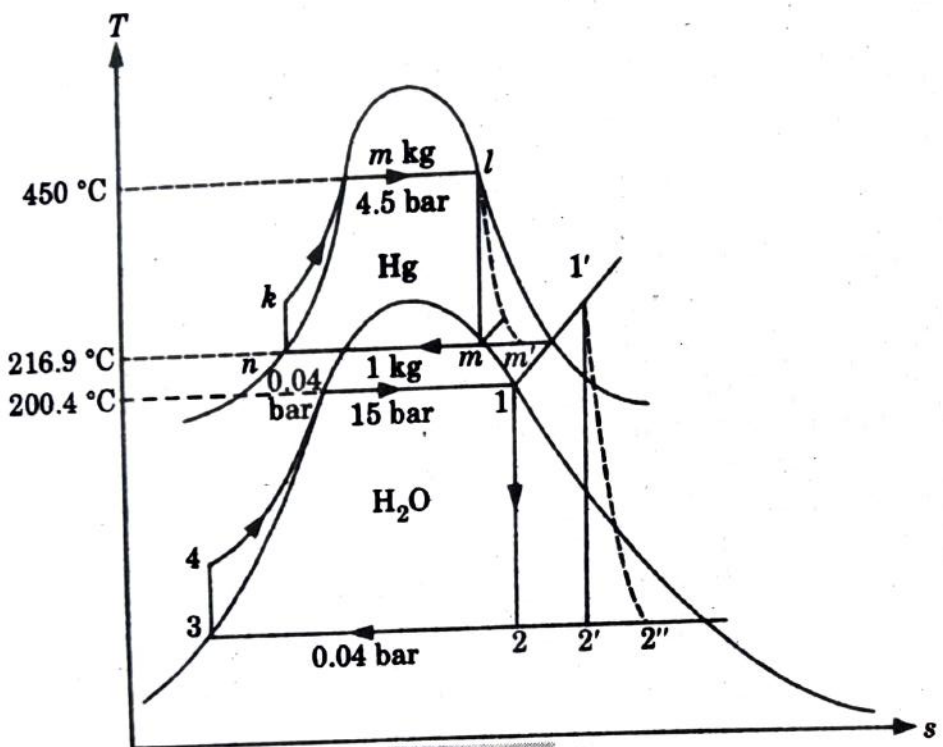


Fig. 2.15.1.

5. For steam cycle,

At 15 bar, $h_1 = 2789.9 \text{ kJ/kg}$, $s_1 = 6.4406 \text{ kJ/kgK}$

At 0.04 bar, $h_f = 121.5 \text{ kJ/kg}$, $h_{fg} = 2432.9 \text{ kJ/kg}$
 $s_f = 0.432 \text{ kJ/kgK}$, $s_{fg2} = 8.052 \text{ kJ/kgK}$
 $v_f = 0.0001 \text{ kJ/kgK}$

6. Now,

$$s_1 = s_2$$

$$6.4406 = s_{f2} + x_2 s_{fg2} = 0.423 + x_2 \times 8.052$$

$$\therefore x_2 = \frac{6.4406 - 0.423}{8.052} = 0.747$$

$$h_2 = h_{f2} + x_2 h_{fg2} = 121.5 + 0.747 \times 2432.9$$

$$= 1938.8 \text{ kJ/kg}$$

7. Work obtained from steam turbine,

$$(W_T)_{\text{steam}} = h_1 - h_2 = 2789.9 - 1938.9 = 851.1 \text{ kJ/kg}$$

8. Pump work in steam cycle,

$$(W_P)_{\text{steam}} = h_{f4} - h_{f3} = 0.001 (15 - 0.04) \times 100 \\ = 1.496 \text{ kJ/kg} \approx 1.5 \text{ kJ/kg}$$

or

$$h_{f4} = h_{f3} + 1.5 = 121.5 + 1.5 = 123 \text{ kJ/kg}$$

$$Q_1 = h_1 - h_{f4} = 2789.9 - 123 = 2666.9 \text{ kJ/kg}$$

$$(W_{\text{net}})_{\text{steam}} = W_T - W_P = 851.1 - 1.5 = 849.6 \text{ kJ/kg}$$

$$\therefore \eta_{\text{steam cycle}} = \frac{W_{\text{net}}}{Q_1} = \frac{849.6}{2666.9} = 0.318 \text{ or } 31.8 \%$$

PART-4

Combined Cycles, Cogeneration.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 2.16. Explain with neat diagrams the working of a combined cycle.

Answer

A. Combined Cycle :

1. Combined cycle is the combination of two cycles, operating on different fluids.
2. The best suited example of combined cycle is gas-steam combined cycle which is a combination of Brayton cycle and Rankine cycle.
3. In a combined cycle, there are two cycles in which first one is high temperature cycle known as topping cycle and second one is low temperature cycle known as bottoming cycle.
4. The heat rejected by topping cycle (Brayton cycle) is recovered in bottoming cycle (Rankine cycle). This heat rejected is used for generation of steam in HRSG (Heat recovery steam generator) or WHRB (Waste heat recovery boiler).
5. Layout for combined cycle is shown in Fig. 2.15.1 consists of following processes :
 - a. **Compression Process :** In process 1-2, compression of air occurs.
 - b. **Heat Addition Process :** In process 2-3, heat addition occurs in combustion chamber.

- c. **Expansion Process** : Expansion process is 3-4, that occurs in turbine.
- d. **Heat Recovery Process** : Exhausts from gas turbine enter into HRSG at state 4 and leave at state 5. The steam generated from HRSG at state 6 is sent to steam turbine for expansion and work output.
6. Let, m_a = Flow rate of air,
 m_f = Flow rate of fuel,
 m_s = Flow rate of steam, and
 CV = Calorific value of fuel.
7. The work done in compressor,
 $W_C = m_a (h_2 - h_1)$
8. Heat addition in combustion chamber,
 $Q_{add} = m_f \times CV$
9. Energy balance in combustion chamber gives
 $m_a \times h_2 + m_f \times CV = (m_a + m_f) h_3$
10. Work available from gas turbine,
 $W_{GT} = (m_a + m_f) (h_3 - h_4)$
- Net work for topping cycle,
 $W_{topping} = W_{GT} - W_C$

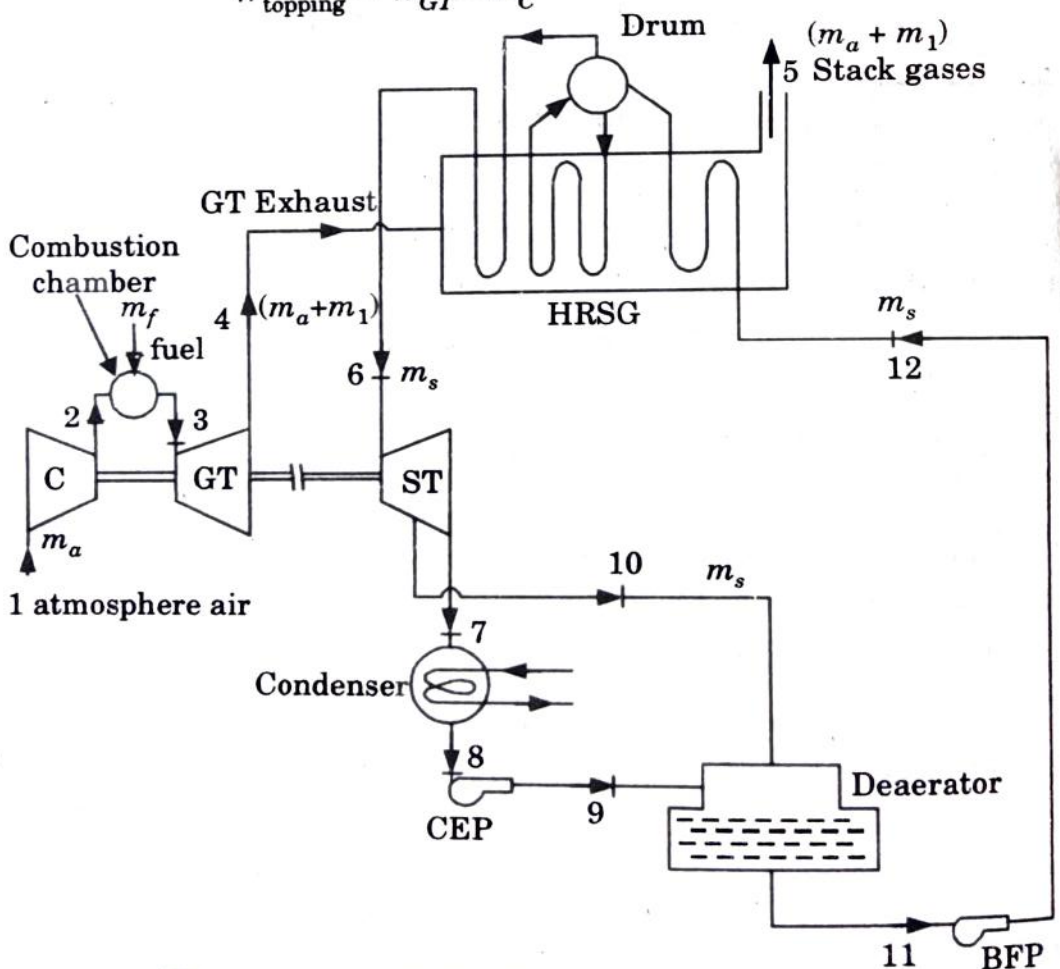


Fig. 2.16.1. Layout of gas-steam combined cycle.

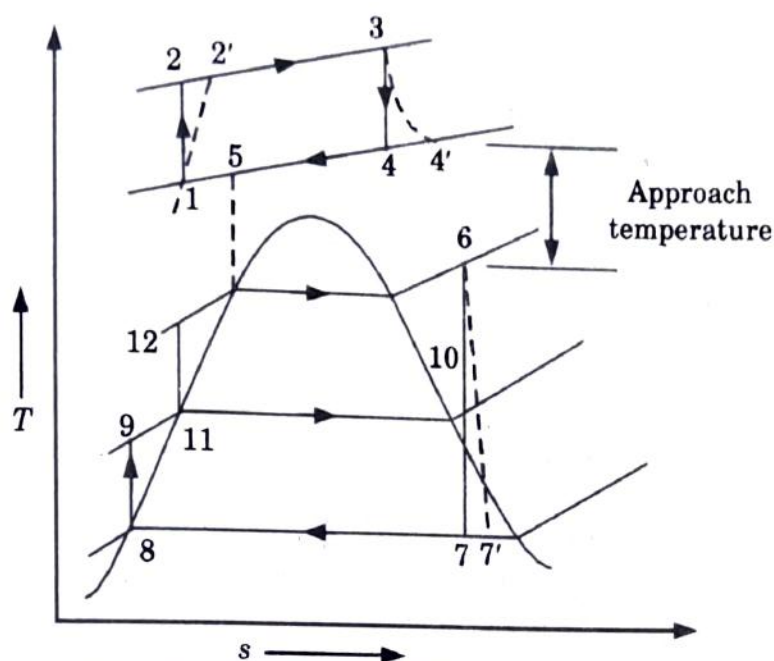


Fig. 2.16.1. *T-s* diagram representation for combined cycle.

11. Work available for steam turbine,

$$W_{ST} = m_s (h_6 - h_7) + (m_s - m'_s) (h_7 - h_{10})$$

Pump work, $W_{CEP} = (m_s - m'_s) (h_9 - h_8)$

$$W_{BFP} = m_s (h_{12} - h_{11})$$

Net work available for bottoming cycle,

$$W_{\text{bottoming}} = W_{ST} - W_{CEP} - W_{BFP}$$

12. Total work for combined cycle,

$$W_{\text{combined}} = W_{\text{bottoming}} + W_{\text{topping}}$$

13. Thermal efficiency of combined cycle,

$$\eta_{\text{combined}} = \frac{W_{\text{combined}}}{Q_{\text{add}}}$$

Que 2.17. Explain cogeneration arrangement. Give its uses also.

Answer

A. Cogeneration :

1. It is defined as an arrangement in which cycle produces work (power) along with heat utilization for process heating.
2. In other words, cogeneration is the arrangement of producing more than one useful form of energy.
3. A schematic arrangement of cogeneration is shown in Fig. 2.17.1.
4. Heat added in boiler,

$$Q_{\text{add}} = m_1 (h_1 - h_9)$$

5. Heat used in process heating,

$$Q_{\text{process}} = m_5 (h_5 - h_7) + m_6 (h_6 - h_7)$$

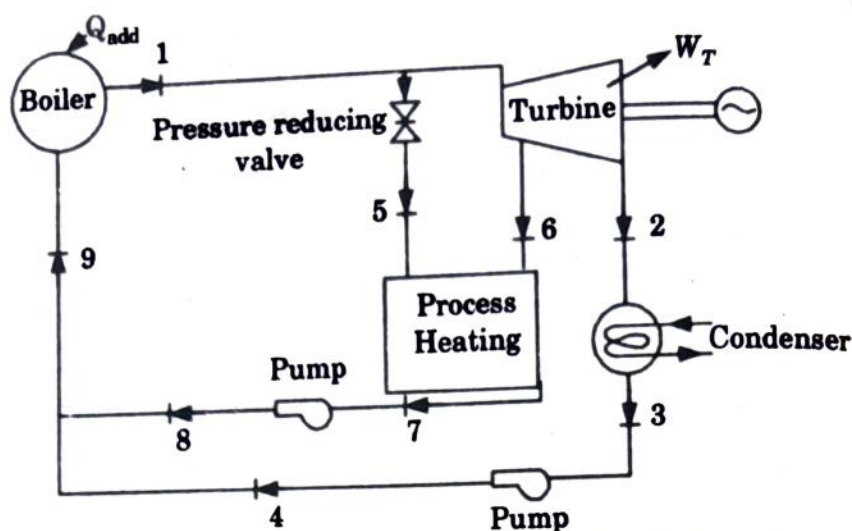


Fig. 2.17.1. Schematic for cogeneration.

6. Turbine work, $W_T = (m_1 - m_5)(h_1 - h_6) + (m_1 - m_5 - m_6)(h_6 - h_2)$
 7. Pump work, $W_P = (m_5 + m_6)(h_8 - h_7) + (m_1 - m_5 - m_6)(h_4 - h_3)$

B. Uses :

1. In food processing industry and chemical industry, steam is required for different processes and electricity too.
2. In cold countries for street heating and electricity supply.

PART-5

Combustion Analysis.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 2.17. Describe various types of combustion analysis.

Answer

Following are the various types of combustion analysis :

a. Ultimate Analysis :

1. The ultimate analysis of a fuel determines the percentage of its components.
2. Fuel consists of carbon, oxygen, hydrogen, nitrogen, sulphur and ash.
3. The percentage of hydrogen and carbon are analyzed by burning of 0.2 gm sample in the atmosphere to produce water vapour and CO_2 as combustion product.

b. Proximate Analysis :

1. The proximate analysis of fuel precisely determines the few important components of solid fuel such as moisture, volatile matter, fixed carbon and ash.
2. It is the technique that separates and identifies categories of compounds in a mixture. These compounds includes moisture and ash content, the extracts of the mixture made of alcohol, petroleum ether, water, hydrochloric acid resins, starches, etc.
3. This type of analysis of solid fuel allows a prediction to be made as to how the fuels will behave in a furnace.

c. Volumetric Analysis :

1. An analysis of gaseous fuels is normally carried out to determine in percent by volume of each element or compound present in the gas.
2. Such an analysis is referred to as volumetric analysis.

PART-6*Heating Values, Air Requirement, Air/Fuel Ratio.***CONCEPT OUTLINE****Air-fuel Ratio (A/F) :** It is used to determine the efficiency of combustion.

$$A/F = \frac{\text{Amount of air}}{\text{Amount of fuel}}$$

Questions-Answers**Long Answer Type and Medium Answer Type Questions****Que 2.19.** Define heating values of fuels.**Answer**

1. The calorific value or heating value of the fuel is defined as the energy liberated by the complete oxidation of a unit mass or volume of a fuel.
2. It is expressed in kJ/kg for solid and liquid fuels and kJ/m³ for gases.
3. The higher heating value, HHV is obtained when the water formed by combustion is completely condensed.
4. The lower heating value, LHV is obtained when the water formed by combustion exists completely in the vapour phase.
5. Thus $(HHV)_p = (LHV)_p + m h_{fg}$... (2.19.1)

$$(\text{HHV})_v = (\text{LHV})_v + m (u_g - u_f) \quad \dots(2.19.2)$$

Where,

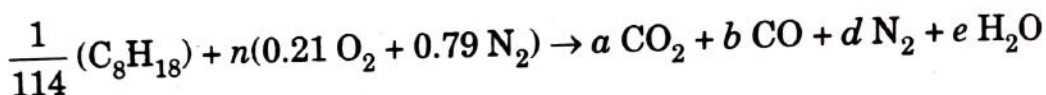
m = Mass of water formed by combustion, kg,
 h_{fg} = Enthalpy of vaporisation of water, kJ/kg,
 u_g = Specific internal energy of vapour, kJ/kg, and
 u_f = Specific internal energy of liquid, kJ/kg.

Que 2.20. One kg C_8H_{18} fuel is supplied to an engine with 13 kg of air. Determine the percentage by volume of CO_2 in dry exhaust gas considering exhaust gas to consist of CO_2 , CO and N_2 .

AKTU 2016-17, Marks 10

Answer

- Combustion equation in molecular basis for one kg of fuel supplied shall be as under,



- Equating the coefficients on both sides,

$$\text{C}; \frac{8}{114} = 0.0702 = a + b$$

$$\text{O}_2; 0.21 n = a + \frac{b}{2} + \frac{e}{2}$$

$$\text{H}; \frac{18}{114} = 0.1579 = 2e$$

$$\text{N}_2; 0.79 n = d$$

- Also it is given that 13 kg of air per kg of fuel is supplied, therefore

$$n = \frac{13}{28.97} = 0.4487$$

- Solving the above equations, we have

$$a = 0.0393, b = 0.0309,$$

$$d = 0.3545, e = 0.07895, n = 0.4487$$

- Constituents of dry exhaust gas shall be CO_2 , CO and N_2 as indicated, Therefore dry exhaust gas = $(a + b + d)$

$$= (0.0393 + 0.0309 + 0.3545) = 0.4247$$

- Percentage by volume of CO_2 in dry exhaust gas

$$= \frac{a}{(a + b + d)} \times 100$$

$$= \frac{0.0393}{0.4247} \times 100 = 9.25 \%$$

Que 2.21.

A sample fuel has the following percentage composition by weight, Carbon = 84 %, Hydrogen = 10 %, Oxygen = 3.5 %, Nitrogen = 1.5 % and Ash = 1 %.

Determine the stoichiometric air fuel ratio by mass.

- i. If 20 % excess air is supplied, find percentage composition of dry fuel gas by volume.

AKTU 2015-16, Marks 10

Answer

Given : Carbon = 84 %, Hydrogen = 10 %, Oxygen = 3.5 %, Nitrogen = 1.5 % and Ash = 1 %

1. On the basis of 100 kg of fuel let us assume an equivalent formula of the form :



2. From the given analysis by weight, we can write

$$12a = 84 \text{ i.e., } a = 7$$

$$1b = 10 \text{ i.e., } b = 10$$

$$16c = 3.5 \text{ i.e., } c = 0.218$$

$$14d = 1.5 \text{ i.e., } d = 0.107$$

3. The formula of fuel is $C_7H_{10}O_{0.218}N_{0.107}$

4. The combustion equation is written as,



5. Then,

Carbon balance : $7 = p \text{ i.e., } p = 7$

Hydrogen balance : $10 = 2q \text{ i.e., } q = 5$

Oxygen balance : $0.218 + 2x = (2p + q)$

$$0.218 + 2x = 2 \times 7 + 5 \text{ i.e., } x = 9.39$$

Nitrogen balance : $0.107 + 2x \left(\frac{79}{21} \right) = 2r$

$$0.107 + 2 \times 9.39 \times \frac{79}{21} = 2r \text{ i.e., } r = 35.4$$

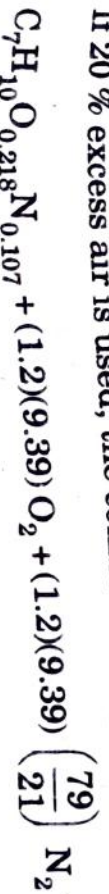
6. Hence the combustion equation becomes,



7. Stoichiometric A/F ratio =

$$\frac{9.39 \times 32 + 9.39 \times \frac{79}{21} \times 28}{100} = 12.89$$

8. If 20 % excess air is used, the combustion equation becomes,



→ $7 \text{ CO}_2 + 5 \text{ H}_2\text{O} + (0.2)(9.39) \text{ O}_2 + (1.2)(35.4) \text{ N}_2$

9. Total number of moles of dry products of combustion,
 $n = 7 + (0.2)(9.39) + (1.2)(35.4)$
 $= 7 + 1.878 + 42.48 = 51.358$

10. Therefore, percentage composition of dry flue gases by volume is as follows :

$$\text{CO}_2 = \frac{7}{51.358} \times 100 = 13.63 \%$$

$$\text{O}_2 = \frac{1.878}{51.358} \times 100 = 3.66 \%$$

$$\text{N}_2 = \frac{42.48}{51.358} \times 100 = 82.71 \%$$

Que 2.22.

Explain the working procedure of the Orsat apparatus for flue gases determination with suitable sketch. Also determine the air fuel ratio of C_3H_8 with 150 percent theoretical air supplied.

AKTU 2017-18, Marks 10

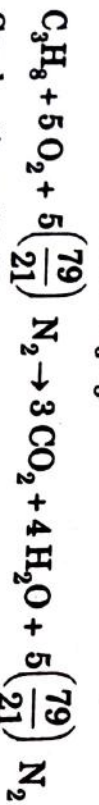
Answer

A. Working Procedure of the Orsat Apparatus : Refer Q. 1.4, Page 1-4A, Unit-1.

B. Numerical :

Given : C_3H_8 with 150 % theoretical air supplied.
 To Find : Air fuel ratio.

1. Normal combustion of C_3H_8 ,



2. Combustion of C_3H_8 with 50 % excess air or 150 % air,



3. Mass of fuel = No. of moles of C_3H_8 × Molecular weight of C_3H_8
 $= 1 \times (3 \times 12 + 8 \times 1) = 44 \text{ kg/mole}$

4. Mass of air = No. of moles of ($\text{O}_2 + \text{N}_2$) × Molecular weight of air

$$= 5 \times 1.5 \times \left[1 + \frac{79}{21} \right] \times 28.97$$

[∵ Molecular weight of air = 28.97]

$$= 1034.64 \text{ kg/mole}$$

5. Air fuel ratio = $\frac{\text{Mass of air}}{\text{Mass of fuel}} = \frac{1034.64}{44} = 23.5 \text{ kg air/kg fuel}$

PART-7

*Standard Heat of Reaction and Effect of Temperature on
Standard Heat of Reaction, Heat of Formation,
Adiabatic Flame Temperature*

CONCEPT OUTLINE

Standard Heat of Reaction : It is equal to the sum of all the standard heats of formation of the products minus the sum of all the standard heats of formation of the reactants.

Adiabatic Flame Temperature : In a combustion process that takes place adiabatically and with no work or changes in kinetic or potential energy, for such a process the temperature of the products is referred as the adiabatic flame temperature.

Questions-Answers**Long Answer Type and Medium Answer Type Questions**

Que 2.23. What do you understand by heat of reaction and heat of formation ?

Answer**A. Heat of Reaction :**

1. If a chemical reaction is carried out at constant pressure and the products are returned to the same initial condition of temperature and pressure as the reactants, the energy released or absorbed by the system is called the enthalpy of reaction or heat of reaction at constant pressure.

B. Heat of Formation :

1. It is defined as the heat released or absorbed when chemical compound is formed from its elements if the temperature of the reactant and product are same.

$$\Delta H_f = H_{\text{compound}} - \sum_i H_i$$

$$\Delta H_f = H_{\text{compound}} - \sum_i (n_i h_i)_{\text{element}}$$

2. The enthalpy of all stable elements in their standard state of 1 atm and 25 °C is assumed to be zero. Hence

$$\Delta H_f = H_{\text{compound}}$$

Que 2.24. Discuss the effect of temperature on standard heat reaction.

AKTU 2014-15, Marks 05

Answer

1. According to the Van't Hoff equation,

$$\frac{d}{dT} \ln K = \frac{\Delta H}{RT^2}$$

This equation can be used to calculate the heat of reaction (ΔH) at a desired temperature.

2. By rearranging the above equation,

$$\frac{d \ln K}{dT} = \frac{\Delta H}{RT^2}$$

$$\therefore \frac{d \ln K}{d(1/T)} = - \frac{\Delta H}{R}$$

$$\therefore \Delta H = -2.303 R \frac{d \log K}{d\left(\frac{1}{T}\right)}$$

$$= -19.148 \frac{d \log K}{d\left(\frac{1}{T}\right)} \text{ kJ/kgmol}$$

3. If K_1 and K_2 are the equilibrium constants at T_1 and T_2 respectively,

$$\therefore \Delta H = -19.148 \frac{\log K_1 - \log K_2}{\frac{1}{T_1} - \frac{1}{T_2}}$$

or

$$\Delta H = -19.148 \frac{T_1 T_2}{T_2 - T_1} \log \frac{K_1}{K_2}$$

4. Thus, the effect of temperature on heat of reaction (ΔH) can be positive or negative. If ΔH is positive, the reaction is said to be endothermic and if ΔH is negative, the reaction is exothermic.

Que 2.25.

What is formation reaction and what standard states are normally used while analyzing chemical reaction ?

Answer

- Formation Reaction:** It is a chemical reaction in which only one mole of a single compound is formed.



B. Standard State Conditions :

1. The standard state temperature should be 25 °C and 1 atm pressure.
2. All liquids should be pure.
3. The concentration of all solutions should be 1 molar.
4. All gases should be pure.
5. The energy of formation of an element in its normal state zero.

VERY IMPORTANT QUESTIONS

Following questions are very important. These questions may be asked in your SESSIONALS as well as UNIVERSITY EXAMINATION.

Q. 1. Draw p - v and T - s diagram for a Rankine cycle. Derive expression for work done and efficiency of cycle. Explain how it is different from modified Rankine cycle ?

Ans. Refer Q. 2.2, Unit-2.

Q. 2. Enumerate effect of pressure and temperature on Rankine cycle.

Ans. Refer Q. 2.5, Unit-2.

Q. 3. A steam engine working on Rankine cycle operates between 1.96 MPa, 250 °C and 13.7 kPa. If engine consumes steam at the rate of 0.086 kg per second, determine Rankine cycle efficiency, neglecting pump work. Also, find Rankine cycle efficiency considering pump work.

Ans. Refer Q. 2.8, Unit-2.

Q. 4. A binary vapour power cycle works on mercury and steam such that dry saturated mercury vapour at 4.5 bar is supplied to mercury turbine and leaves at 0.04 bar. Steam is generated as dry saturated at 15 bar and supplied to steam turbine for being expanded upto condenser pressure of 0.04 bar. Determine thermal efficiency of cycle. For mercury take, h_f at 4.5 bar = 62.93 kJ/kg, h_g at 4.5 bar = 355.98 kJ/kg, v_f at 0.04 bar = 0.0000765 m³/kg, h_f at 0.04 bar = 29.98 kJ/kg, h_g at 0.04 bar = 329.85 kJ/kg, s_g at 4.5 bar = 0.5397 kJ/kgK, s_g at 0.04 bar = 0.6925 kJ/kgK, s_f at 0.04 bar = 0.0808 kJ/kgK.

Ans. Refer Q. 2.15, Unit-2.

Boilers and Condenser

CONTENTS

Part-1 :	Classification and Working of Boilers	3-2A to 3-5A
Part-2 :	Boiler Mounting and Accessories	3-5A to 3-11A
Part-3 :	Draught and its calculations	3-11A to 3-17A
Part-4 :	Air Preheater, Feed Water Heater, Superheater	3-17A to 3-19A
Part-5 :	Boiler Efficiency, Equivalent Evaporation, Boiler Trial and Heat Balance	3-19A to 3-24A
Part-6 :	Classification of Condenser, Air Leakage	3-25A to 3-27A
Part-7 :	Condenser Performance Parameters	3-27A to 3-29A

PART-1*Classification and Working of Boilers.***Questions-Answers****Long Answer Type and Medium Answer Type Questions****Que 3.1.**

What are boilers ? How are they classified ?

Answer**A. Boiler :**

1. A boiler is defined as the combination of apparatus for producing furnishing or recovering close heat together with apparatus for transferring the heat so made available to the fluid being heated and vapourized.

2. It is a closed vessel in which fluid is heated. The heated or vapourized fluid exits the boiler for use in various heating processes.

B. Classification of Boilers :**a. Based upon the Orientation/Axis of the Shell :**

1. Vertical boiler,
2. Horizontal boiler, and
3. Inclined boiler.

b. Based Upon Utility of Boiler :

1. Stationery boiler, and
2. Portable boiler.

c. Based on Type of Firing Employed :

1. Externally fired boilers, and
2. Internally fired boilers.

d. Based Upon the Tube Content :

1. Fire tube boilers, and
2. Water tube boilers.

e. Based on Type of Fuel Used :

1. Solid fuel fired boilers,
2. Liquid fuel fired boilers, and
3. Gas fired boilers.

Based on Circulation :

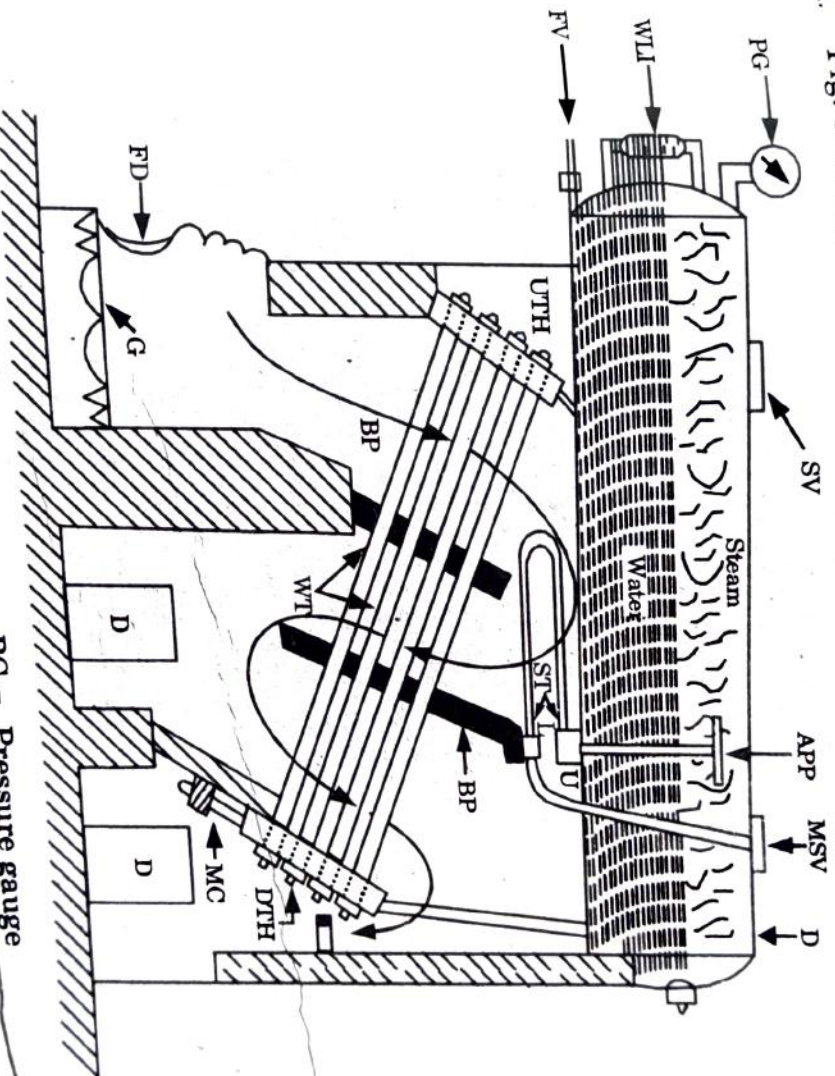
- f. Natural circulation boilers, and
1. Forced circulation boilers.
- 2.

Que 3.2.**With the help of a neat sketch explain Babcock and Wilcox boiler.****AKTU 2016-17, Marks 10**

boiler.

Answer

1. Fig. 3.2.1 shows the Babcock and Wilcox water tube boiler.



D = Drum	PG = Pressure gauge
DTH = Down take header	ST = Superheater tubes
WT = Water tubes	SV = Safety valve
BP = Baffle plates	MSV = Main stop valve
D = Doors	APP = Antipriming pipe
G = Grate	L = Lower junction box
FD = Fire door	U = Upper junction box
MC = Mud collector	FV = Feed valve
WLI = Water level indicator	

Fig. 3.2.1. Babcock and Wilcox boiler.

2. It consists of a drum connected to a series of front end and end header by short rising tubes.
3. A horizontal water drum is the main part of boiler. It is supported by steel structure at certain height and independent of brick work.

3-4 A (ME-Sem-4)

4. The size of the boiler drum is small as compared to boiler drum of fire tube boiler of same capacity. It contains water and steam.
5. All safety and control devices are mounted over the drum for proper functioning.
6. A feed valve is provided to fill the drum and inclined tubes with water, and level of which is indicated by water level indicator.
7. The water from the drum flows through the inclined tubes via down take header and goes into the shell in the form of vapour and water.

Que 3.3. Explain the working of fire tube boilers in reference with Lancashire boiler with neat sketch.

Answer

1. Fuel is burnt at the grate. The water is pumped into the shell through the economiser which increases the temperature of water.
2. Now the shell is half filled with water. The fire tube is fully immersed into the water.
3. The fuel is charged at the grate which produces flue gases. These flue gases first passes through the fire tube from one end to another. This fire tubes transfer 80-90 % of total heat to the water.
4. The steam produces in drum shell it taken out from the upper side where it flows through super heater if required. So the steam produce is taken by cut for process work.

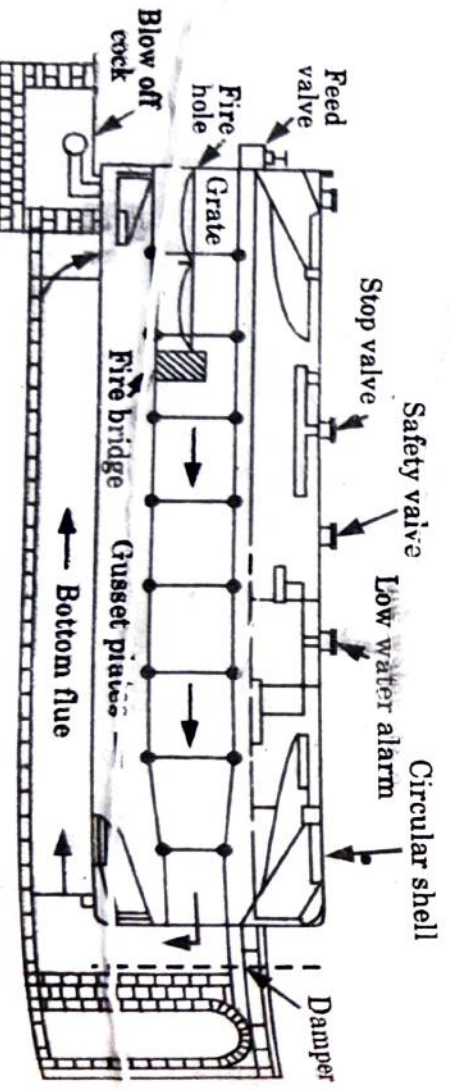


Fig. 3.3.1. Lancashire boiler.

Que 3.4. What are the essentials of a good boiler ? Distinguish between fire tube and water tube boiler. Give two names of each. Give a neat labelled sketch of a Babcock and Wilcox boiler.

Answer**A. Essentials of a Good Boiler :**

1. It should be easy to install.
2. It should produce maximum amount of steam with given amount of fuel.
3. It should be light in weight.
4. It should rapidly meet fluctuation of load.
5. Less frictional losses in circulation of water and flue gas.

B. Difference between Fire Tube and Water Tube Boiler :

S.No.	Particulars	Water Tube Boiler	Fire Tube Boiler
1.	Position of water and hot gases	Water circulates inside the tubes which are surrounded by hot gases from the furnace.	The hot gases from the furnace pass through the tubes which are surrounded by water.
2.	Modes of fire	Externally fired.	Internally fired.
3.	Rate of steam production	The rate of generation of steam is high.	The rate of generation of steam is low.
4.	Cost	The operating cost is high.	The operating cost is low.
5.	Suitability	It is preferred for large power plant.	It is not suitable for large power plant.
6.	Operating pressure	High (as 100 bar).	Low (up to 16 bar).
7.	Floor area	It requires more floor area.	Less floor area is required.
8.	Transportation	It can be transported easily as its various parts can be separated.	Transportation is difficult.
9.	Examples	Babcock and Wilcox, Stirling.	Locomotive boilers, Lancashire.

C. Babcock and Wilcox Boiler : Refer Q. 3.2, Page 3-3A, Unit-3.

PART-2

CONCEPT OUTLINE

Boiler Mountings : These are different fittings and devices which are necessary for the operation and safety of a boiler. These mountings form an integral part of the boiler.

Boiler Accessories : These are the auxiliary plants required for steam boilers for their proper operation and for the increase of their efficiency.

Questions-Answers**Long Answer Type and Medium Answer Type Questions****Que 3.5.**

Explain the working of water level indicator, safety valves, and fusible plug, feed check valve, pressure gauge, stop valve and blow off cock.

AKTU 2018-19, Marks 10**OR**

Explain following mountings :

- a. Water level indicator.
- b. Pressure gauge.
- c. Feed check valve.
- d. Blow off cock.
- e. Fusible plug.
- f. Safety valves.
- g. Stop valve.

Answer

A. Water Level Indicator :

1. The function of water level indicator is to indicate the level of water in the boiler constantly.
2. General arrangement of water level indicator is shown in Fig. 3.5.1.

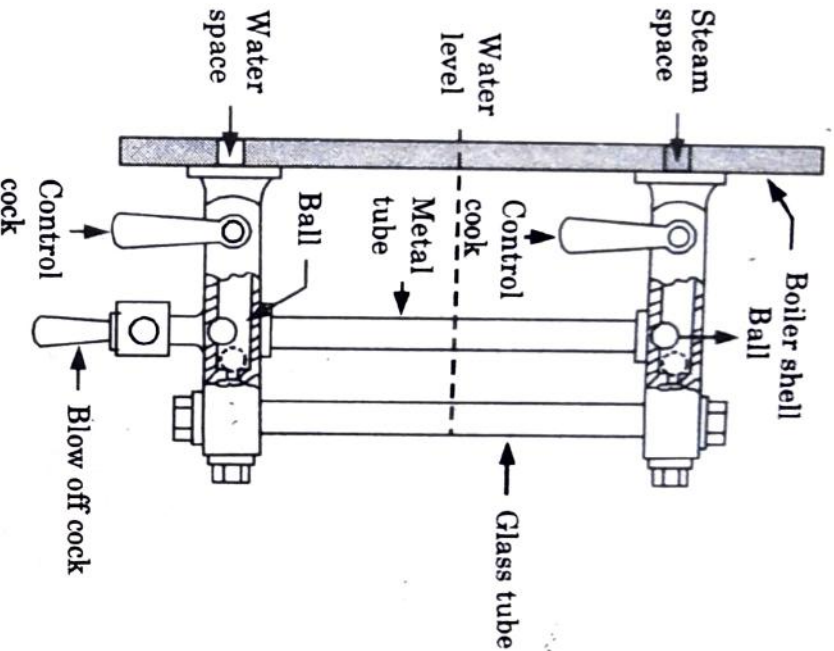


Fig. 3.5.1. Water level indicator.

3. It has two tubes one is front glass tube while other is metal tube, where the boiler drum situated at considerable height from the floor water gauges often inclined to make the water level visible from any position.
4. Two control cocks are provided for regulating steam and water passes from the boiler to glass tube.
5. When the water being heated in the boiler transformed into steam the level of water in the boiler shell goes on reducing.

B. Safety Valves :

1. Its function is to prevent the steam pressure from exceeding a limiting maximum pressure value.
2. Safety valve should operate automatically by releasing excess steam and bring pressure down within safe limits.
3. These are of different types such as dead weight safety valve, lever safety valve, spring loaded safety valve etc.
4. Fig. 3.5.2 gives the general description of dead weight safety valve. It has a large vertical pipe on the top of which a valve seat is fixed. Valve rests upon this valve seat.

5. A weight carrier is hung on the top valve upon which cast iron rings enclosed in cast iron cover are placed in weight carrier as dead weight.

7. When the pressure of steam exceeds the total weight of valve, it is lifted and falls back as steam pressure gets reduced.

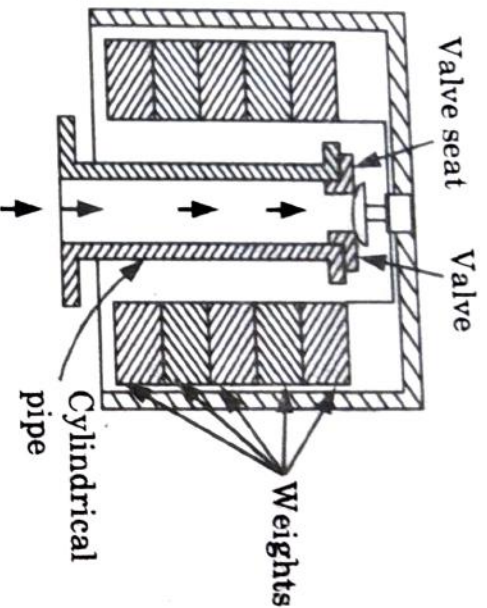


Fig. 3.5.2. Dead weight safety valve.

C. Fusible Plug:

1. Fusible plug has gun metal body. Fig. 3.5.3 shows the arrangement of fusible plug.
2. Function of a fusible plug is to protect the boiler against the damage due to overheating at low water level.
3. Under normal conditions when the water level in the boiler shell is normal, the fusible plug is fully submerged under water.
4. In this case, the heat from the fusible plug conducted to water which keeps the fusible metal at an almost constant temperature below its melting point.

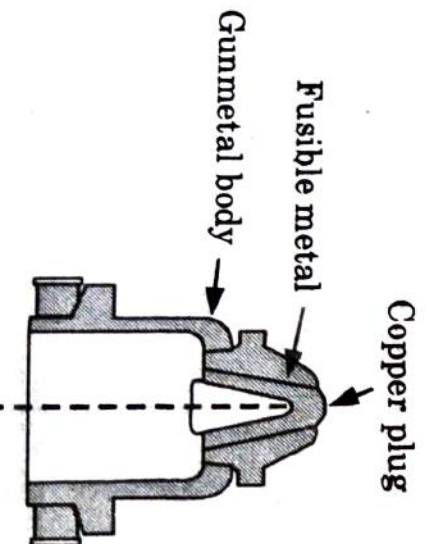


Fig. 3.5.3. Fusible plug.

D. Feed Check Valve:

1. It is a non-return valve at the end of delivery pipe from feed water pump.
2. This may be fitted on the side of boilers just below the water level or to the top level of the water in boiler.

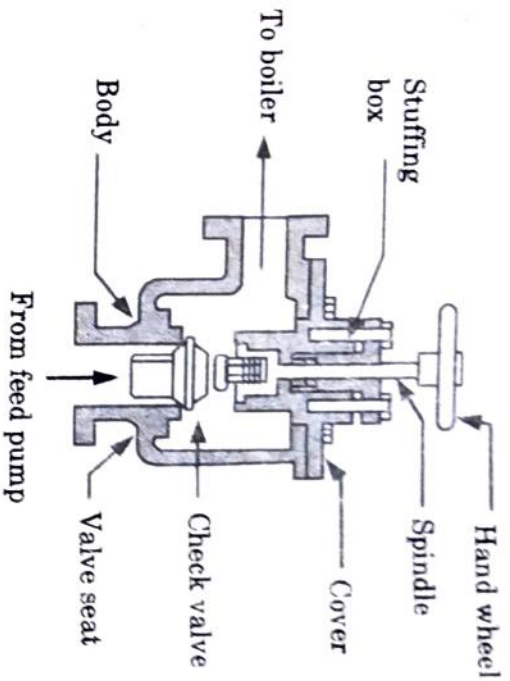


Fig. 3.5.4. Feed check valve.

3. The function of feed check valve is to allow the supply of water to the boiler at high pressure continuously and to prevent the back flow of water from the pump pressure is less than boiler pressure or when pump fails.

E. Pressure Gauge :

1. It is mounted at the front top of the boiler drum. Generally Bourdon tube pressure gauges are being used for pressure measurement.
2. It is usually constructed to indicate upto double the maximum working pressure.
3. The dial is graduated to read pressure in bar or MPa gauge.

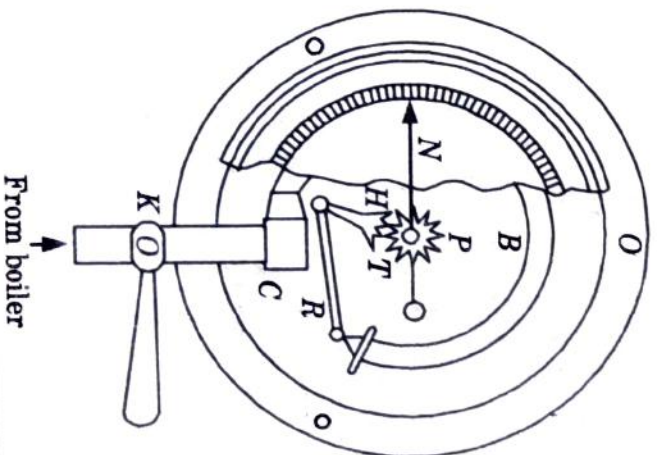


Fig. 3.5.5. Bourdon tube pressure gauge.

F. Stop Valve :

1. It regulates the flow of steam from the boiler as shown in Fig. 3.5.6.

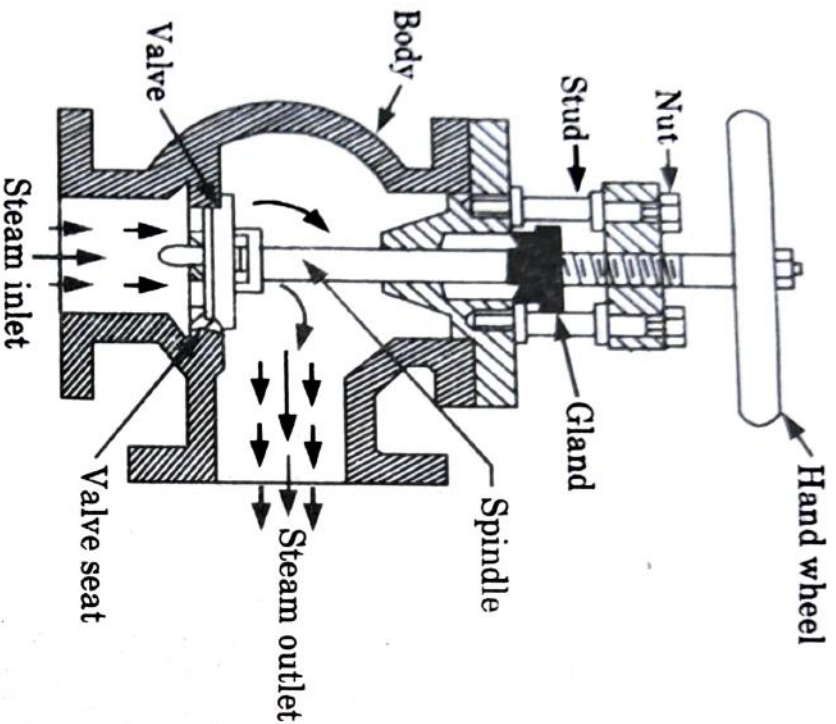


Fig. 3.5.6. Stop valve.

2. This is generally mounted on highest part of boiler shell and performs function of regulating the flow of steam from boiler.
3. Stop valve generally has main body of cast steel, valve, valve seat and nut etc. are of brass.
4. Stop valve can be easily operated by rotating the hand wheel which causes lifting or lowering of spindle, thus causing opening or closing of valve.

G. Blow Off Cock :

1. Its valve fitted on the boiler shell directly or a short branch pipe at the lowest part of water space.
2. It is used for periodical cleaning by discharging water and sediments from bottom.
3. Blow off cock also helps in regulating the salt concentration as frequent draining helps in throwing out the salt deposited.

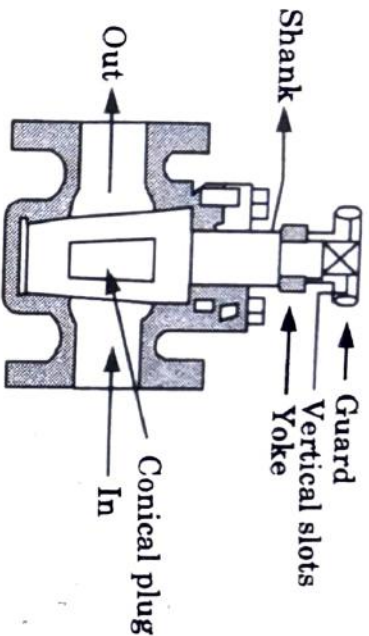


Fig. 3.5.7. Blow off cock.

Que 3.6. What are boilers ? How are they classified ? Differentiate between mountings and accessories. **AKTU 2014-15, Marks 10**

Answer

A. Boilers and their Classification : Refer Q. 3.1, Page 3-2A, Unit-3.
 B. Difference between Mountings and Accessories :

S.No.	Mountings	Accessories
1.	Devices which are used for the safety and operation of boiler are known as mountings.	Devices which are used to improve the efficiency of boilers are known as accessories.
2.	These are generally mounted on the surface of boiler.	These are integral part of boiler, but not mounted on it.
3.	Control fluid parameters at the inside of the boiler shell.	Control fluid parameters at outside of boiler shell.
4.	These are essential part of a boiler, without which boiler operation is impossible.	These are not essential part of the boiler, without which boiler can operate though at lower efficiency.
5.	Example : Water level indicator, pressure gauge, safety valve.	Example : Superheaters, economizer, air preheater.

PART-3

Draught and its Calculations.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 3.7. What do you understand by boiler draught ? Calculate condition for maximum discharge.

AKTU 2014-15, Marks 10

Answer

A. Boiler Draught :

1. The flow of flue gases in chimney due to difference in pressure between cold atmospheric air outside and hot gases in chimney is known as boiler draught.
2. Draught may be created naturally or by using external device.

B. Condition for Maximum Discharge :

1. The chimney draught is most effective when the maximum weight of hot gases is discharged in a given time, and it will be shown that this occurs when the absolute temperature of the chimney gases bears a certain relation to the absolute temperature of the outside air.
2. We know that the velocity of gas through the chimney, assuming the losses to be negligible is given by,

$$C = \sqrt{2gH_1} \quad \dots(3.7.1)$$

and
$$H_1 = H \left[\left(\frac{m_a}{m_a + 1} \right) \frac{T_g}{T_a} - 1 \right] \quad \dots(3.7.2)$$

3. Putting value of H_1 in eq. (3.7.1), we get,

$$C = \sqrt{2gH \left[\left(\frac{m_a}{m_a + 1} \right) \frac{T_g}{T_a} - 1 \right]} \quad \dots(3.7.3)$$

4. The density of the hot gases is given by,

$$\rho_g = \frac{p}{RT_g} \quad \dots(3.7.4)$$

5. The mass of gas discharge per second,

$$m_g = AC\rho_g \quad \dots(3.7.5)$$

6. From eq. (3.7.3), eq. (3.7.4) and eq. (3.7.5), we get

$$m_g = A \sqrt{2gH \left[\left(\frac{m_a}{m_a + 1} \right) \frac{T_g}{T_a} - 1 \right]} \frac{p}{RT_g}$$

$$m_g = \frac{K}{T_g} \sqrt{\left(\frac{m_a}{m_a + 1}\right) \frac{T_g}{T_a} - 1}$$

Where,

$$K = \text{Constant} = \frac{Ap\sqrt{2gH}}{R}$$

7. The value of m_g will be maximum, if

$$\frac{dm_g}{dT_g} = 0$$

$$\frac{d}{dT_g} \left[\frac{K}{T_g} \sqrt{\left(\frac{m_a}{m_a + 1}\right) \frac{T_g}{T_a} - 1} \right] = 0$$

$$\frac{d}{dT_g} \left[\frac{1}{T_g} \sqrt{\left(\frac{m_a}{m_a + 1}\right) \frac{T_g}{T_a} - 1} \right] = 0$$

$$\frac{d}{dT_g} \left[\frac{(zT_g - 1)^{1/2}}{T_g} \right] = 0$$

Where,

$$z = \left(\frac{m_a}{m_a + 1}\right) \frac{1}{T_a}$$

$$\frac{d}{dT_g} [(zT_g - 1)^{1/2} \times T_g^{-1}] = 0$$

$$\frac{-(zT_g - 1)^{1/2}}{T_g^2} + \frac{z}{2T_g(zT_g - 1)^{1/2}} = 0$$

$$\frac{-2(zT_g - 1) + zT_g}{2(T_g)^2 (zT_g - 1)^{1/2}} = 0$$

$$-2(zT_g - 1) + zT_g = 0$$

$$zT_g = 2$$

$$\left(\frac{m_a}{m_a + 1}\right) \frac{T_g}{T_a} = 2$$

$$\frac{T_g}{T_a} = 2 \left(\frac{m_a + 1}{m_a}\right)$$

8. Thus, we see that the absolute temperature of the chimney gases wears a certain ratio to the absolute temperature of the outside air.
9. Putting the value of $\frac{T_g}{T_a}$ in eq. (3.7.2), we get

$$(H_1)_{\max} = H \left[\left(\frac{m_a}{m_a + 1} \right) \times 2 \left(\frac{m_a + 1}{m_a} \right) - 1 \right]$$

$$= H (2 - 1) = H$$

$$(H_1)_{\max} = H$$

Que 3.8. Obtain the expression for the natural draught in terms of height of water column.

Answer

1. Assume that the volume of fuel combustion is equal to the volume of air to the same pressure and temperature.

m_a = Mass of air per kg of fuel,

$m_a + 1$ = Mass of chimney gases,

T_a = Absolute temperature of atmosphere, and

T_g = Absolute temperature of chimney gases.

2. Also, $\frac{\text{Mass of chimney gases}}{\text{Mass of air}} = \frac{m_a + 1}{m_a}$

3. Now, pressure density of air,

$$\rho_a = \frac{p}{RT_a} = \frac{1.01325 \times 10^5}{287 \times T_a} = \frac{353}{T_a}$$

4. Pressure density of gases, $\rho_g = \frac{\rho}{RT_g} \left[\frac{m_a + 1}{m_a} \right]$
- $$= \frac{353}{T_g} \left[\frac{m_a + 1}{m_a} \right]$$

5. We know that net pressure difference,

$$\Delta p = (\rho_a - \rho_g) gH$$

Putting the value of ρ_a and ρ_g into eq. (3.8.1),

...(3.8.1)

$$\Delta p = 353gH \left[\frac{1}{T_a} - \frac{1}{T_g} \left(\frac{m_a + 1}{m_a} \right) \right] \text{ N/m}^2$$

...(3.8.2)

Where, H is the height of chimney

6. Assume the draught pressure Δp produced is equivalent to H_1 metre height of burnt gases.

$$\Delta p = \rho_g g H_1 = 353 \left[\frac{m_a + 1}{m_a} \right] \frac{1}{T_g} gH_1$$

...(3.8.3)

7. Equating eq. (3.8.2) and eq. (3.8.3), we get

$$353 \left[\frac{m_a + 1}{m_a} \right] \frac{1}{T_g} gH_1 = 353gH \left[\frac{1}{T_a} - \frac{1}{T_g} \left(\frac{m_a + 1}{m_a} \right) \right]$$

$$\frac{353}{T_g} \left[\frac{m_a + 1}{m_a} \right] gH_1 = \frac{353}{T_a} gH - \frac{353}{T_g} gH \left[\frac{m_a + 1}{m_a} \right]$$

$$H_1 = H \left[\left(\frac{m_a}{m_a + 1} \right) \frac{T_g}{T_a} - 1 \right]$$

8. Due to friction losses, actual draught available is always less than that given by eq. (3.8.2).
9. If h_w is height in mm of column of water which will produces the pressure difference, then,

$$h_w = 353H \left[\frac{1}{T_a} - \frac{1}{T_g} \left(\frac{m_a + 1}{m_a} \right) \right]$$

Que 3.9. A boiler may have waste gases leaving the installation

when artificial draught is used at 150 °C. The natural draught chimney is of 60 m height. The hot gases within chimney are at temperature of 300 °C and air requirement is 19 kg per kg of fuel burnt. The atmospheric air is at 17 °C temperature and mean specific heat of hot gases is 1.0032 kJ/kgK. The calorific value of fuel burnt is 32604 kJ/kg. Determine :

- i. The draught produced in mm of water,
- ii. The efficiency of chimney, and
- iii. The extra heat carried away by flue gases per kg of fuel.

AKTU 2016-17, Marks 10

Answer

Given : $T_g = T' = 300 + 273 = 573 \text{ K}$, $T_a = 17 + 273 = 290 \text{ K}$,
 $T'' = 150 + 273 = 423 \text{ K}$, $H = 60 \text{ m}$, $m = 19 \text{ kg/kg of fuel}$,
 $C_p = 1.0032 \text{ kJ/kgK}$

1. We know that,

$$\begin{aligned} h_w &= 353 H \left[\frac{1}{T_a} - \left(\frac{m + 1}{m} \right) \frac{1}{T_g} \right] \\ &= 353 \times 60 \times \left[\frac{1}{290} - \left(\frac{19 + 1}{19} \right) \times \frac{1}{573} \right] \\ &= 34.13 \text{ mm of water} \end{aligned}$$

$$9.81 H \left\{ \left(\frac{m}{m + 1} \right) \frac{T_g}{T_a} - 1 \right\}$$

2. Chimney efficiency = $\frac{9.81 H \left\{ \left(\frac{m}{m + 1} \right) \frac{T_g}{T_a} - 1 \right\}}{C_p \times (T' - T'')}$

$$= \frac{9.81 \times 60 \times \left\{ \left(\frac{19}{19+1} \right) \times \frac{573}{290} - 1 \right\}}{1.0032 \times (573 - 423) \times 10^3}$$

$$= 3.431 \times 10^{-3} \text{ or } 0.3431 \%$$

3. Extra heat carried by flue gases per kg of fuel burnt

$$= (m+1) C_p \times (T' - T'') \quad [\because m = 19]$$

$$= 20 \times 1.0032 \times (573 - 423)$$

$$= 3009.6 \text{ kJ/kg of fuel}$$

Que 3.10. Calculate the mass of the flue gases flowing through chimney when the draught produced is equals to 1.9 cm of water. Temperature of the flue gas is 290 °C and the ambient temperature is 20 °C. The flue gas formed per kg of fuel burnt are 23 kg. Neglect the losses and take the diameter of the chimney as 1.8 m.

AKTU 2017-18, Marks 10

Answer

Given : $h_w = 1.9 \text{ cm} = 19 \text{ mm}$, $T_g = 290^\circ\text{C} = 290 + 273 = 563 \text{ K}$

$T_a = 20^\circ\text{C} = 20 + 273 = 293 \text{ K}$, $(m_a + 1) = 23 \text{ kg}$, $D = 1.8 \text{ m}$

To Find : Mass of the flue gases passing through chimney.

1. We know that,

$$h_w = 353 H \left[\frac{1}{T_a} - \frac{1}{T_g} \left(\frac{m_a + 1}{m_a} \right) \right]$$

$$19 = 353 H \left(\frac{1}{293} - \frac{1}{563} \times \frac{23}{22} \right)$$

$$\left(\because m_a + 1 = 23 \text{ kg} \right)$$

$$\left(\text{i.e., } m_a = 22 \text{ kg} \right)$$

$$19 = 353 H (0.00341 - 0.00185) = 0.55 H$$

or

$$H = 34.54 \text{ m}$$

2. Using the relation, $H_1 = H \left[\left(\frac{m_a}{m_a + 1} \right) \left(\frac{T_g}{T_a} \right) - 1 \right]$

Where,

$H_1 = \text{Head in terms of gas column.}$

$\therefore$

$$H_1 = 34.54 \left[\left(\frac{22}{23} \times \frac{563}{293} \right) - 1 \right] = 28.94 \text{ m of air}$$

3. Velocity of gases,

$$C = \sqrt{2gH_1} = \sqrt{2 \times 9.81 \times 28.94} = 23.83 \text{ m/s}$$

4. Now, mass of flue gases,

$$m_g = AC\rho_g$$

Where,

$$\rho_g = 353 \left(\frac{m_a + 1}{m_a} \right) \frac{1}{T_g}$$

$$= 353 \times \frac{23}{22} \times \frac{1}{563} = 0.655 \text{ kg/m}^3$$

$$\therefore m_g = \pi/4 \times (1.8)^2 \times 23.83 \times 0.655 = 39.8 \text{ kg/s}$$

PART-4

Air Preheater, Feed Water Heater, Superheater.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 3.11. Explain the following in brief with suitable sketch :

- Economiser.
- Air preheater.
- Superheater.

Answer

a. **Economiser :**

- The economiser preheats the boiler feed water before it enters the boiler drum by recovering heat from the flue gases.
- In economiser, water is heated to about 30 to 40 °C below saturation temperature.
- Economiser is located in the boiler rear gas pass ahead of air preheaters and following the primary superheater or reheater in the gas stream.
- Economiser coils are designed for horizontal placement which facilitates draining of the coil.
- The water in the economiser tubes flows in upward direction and gas in the downward direction.
- Water flow is from bottom to top so that steam if any formed during the heat transfer can move along with water and prevent the lock up steam which will cause overheating and failure of economiser tube.

Fig. 3.11.1. Economiser coil and the temperature profiles of flue gas and water.

b. Air Preheater :

1. An air preheater is shown in the Fig. 3.11.2. Hot flue gases pass through the tubes and cold air passed over these tubes.

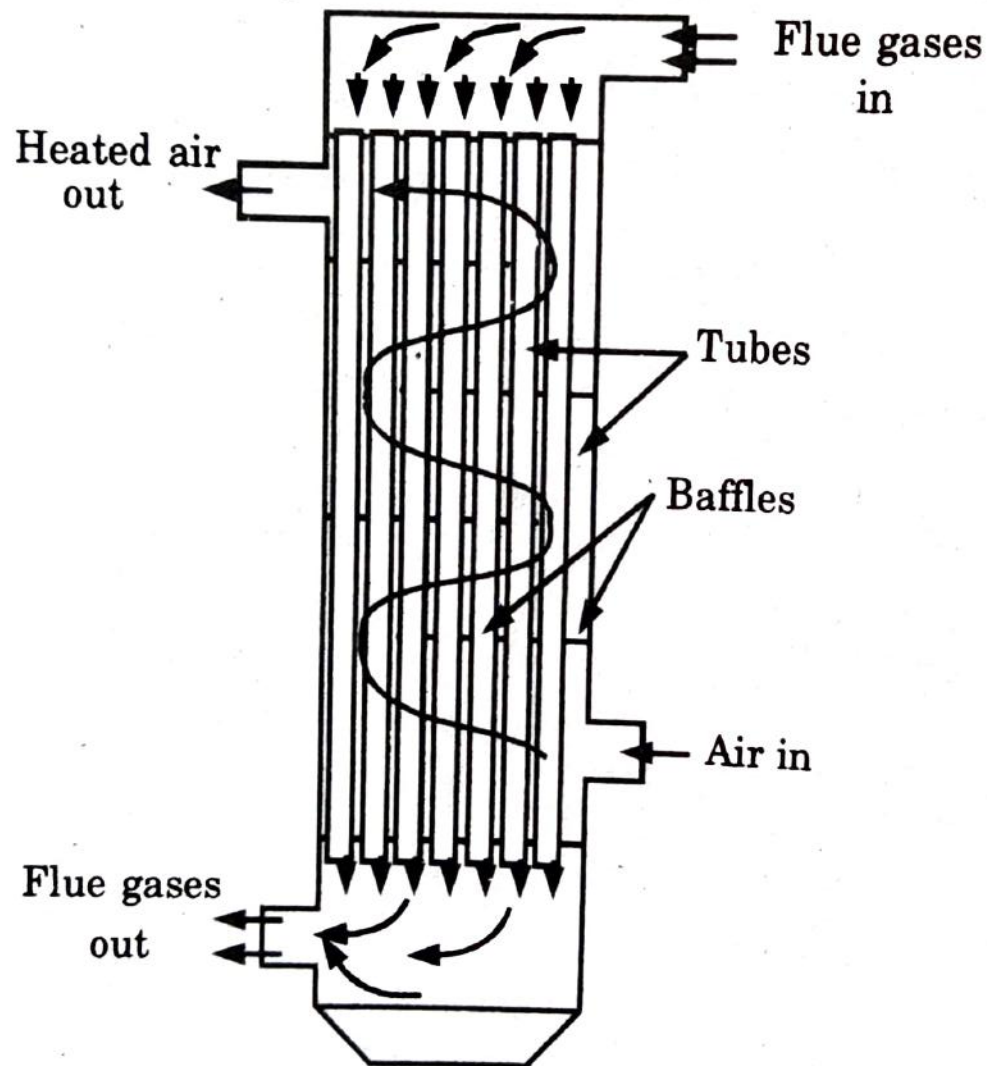


Fig. 3.11.2. Air preheater.

2. The baffles are provided to improve the duration of time contact for proper heat transfer between hot gases and cold air.
 3. The flue gases are finally discharged to chimney from the air preheater at lower temperature, allowing simplified design of the ducting and flue gases stack.
 4. The purpose of the air preheater is to recover the heat from the boiler flue gases which improve the efficiency of boiler by reducing the useful heat lost in the flue gases.
- c. Superheater :**
1. The function of a superheater is to increase the temperature of the steam above its saturation point.

2. The superheater is very important accessory of a boiler and can be used both on fire tube and water tube boilers.
3. The small boilers are not commonly provided with a superheater.
4. Superheaters are located in the path of the furnace gases so that heat is recovered by the superheater from the hot gases.
5. There are two types of superheaters :
 - i. **Convective Superheater** : It makes use of heat in flue gases.
 - ii. **Radiant Superheater** : It is placed in the furnace and wall tubes receives heat from the burning fuel through radiant process.

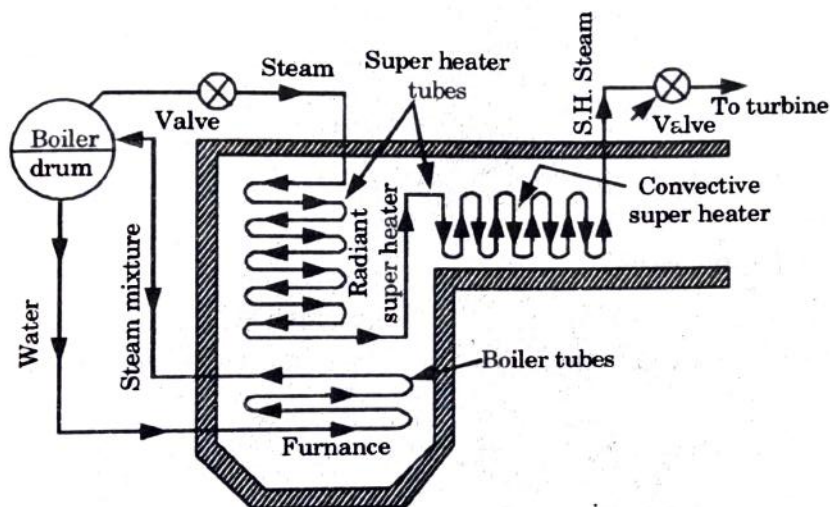


Fig. 3.11.3. Superheater.

PART-5

*Boiler Efficiency, Equivalent Evaporation,
Boiler Trial and Heat Balance.*

CONCEPT OUTLINE

Heat Balance Sheet : The heat balance sheet is a symmetric representation of heat released from burning of fuel and heat distribution on minute, hour or per kg of fuel basis.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 3.12. Write short note on the following :

- i. Boiler Efficiency.
- ii. Equivalent Evaporation.

Answer**A. Equivalent Evaporation :**

1. It is defined as the amount of water evaporated from water at 100 °C to dry and saturated steam at 100 °C.
2. Consider a boiler generating m_a kg of steam per hour at a pressure p and temperature T .
3. Let h = Enthalpy of steam per kg under the generating conditions.
 h_{f1} = Specific enthalpy of water at a given feed temperature.
4. Heat gained by the steam from the boiler per unit time
 $= m_a (h - h_{f1})$
5. The equivalent evaporation (m_e) from the definition is obtained as

$$m_e = \frac{m_a (h - h_{f1})}{h_{fg}} = \frac{m_a (h - h_{f1})}{2257}$$

B. Boiler Efficiency :

1. Boiler efficiency is the ratio of heat actually utilized in generation of steam to the heat supplied by the fuel in the same period.

$$\text{Boiler efficiency} = \frac{m_a (h - h_{f1})}{CV}$$

Where,

m_a = Mass of water actually evaporated into steam per kg of fuel at the working pressure, and

CV = Calorific value of the fuel in kJ/kg.

Que 3.13. What is meant by boiler trial? What measurement should be observed during the boiler trial?

Answer**A. Boiler Trial :**

1. It refers to run the boiler under test conditions for its efficiency estimation.
2. It shows the steam generation rate of boilers, thermal efficiency of plant and heat balance sheet of plant.
3. Under the trial the boiler is run for quite long period so as to attain steady state.

B. Measurement Observed During Boiler Trial : The following measurements should be observed during the boiler trial :

1. The fuel supplied and its analysis.
2. Steam generated and its quality of superheat.
3. Flue gases formed from exhaust analysis.

4. Air inlet temperature and gases exhaust temperature.
5. Volumetric analysis of exhaust in ash.
6. Mass of fuel unburnt in ash.
7. Feed water temperature.

Que 3.14. Define heat balance on boiler with various heat losses.

Answer

A. Heat Balance : Heat balance on boiler refers to the accounting for total heat released inside boiler and its distribution.

B. Heat Losses in a Boiler Plant :

a. **Heat used to Generate Steam :** $Q_1 = m_s(h - h_{f1})$

b. **Heat Lost due to Flue Gases :**

$$Q_2 = m_g C_{pg} (T_g - T_a) \text{ (due to dry flue gases)}$$

Where,

m_g = Mass of gases formed per kg of coal,

C_{pg} = Specific heat of gases,

T_g = Temperature of the gases, and

T_a = Temperature of air entering the combustion chamber of boiler.

c. **Heat Carried away by Steam in Flue Gases :**

$$Q_3 = m_{s1} (h_{s1} - h_{f1})$$

Where,

m_{s1} = Mass of steam formed per kg of fuel due to the combustion of H_2 in the fuel,

h_{f1} = Enthalpy of water at boiler house temperature, and

h_{s1} = Enthalpy of steam at the gas temperature and partial pressure of steam vapour.

d. **Heat Lost due to Incomplete Combustion :**

$$Q_4 = \frac{CO \times C}{CO_2 + CO} \times 23680 \text{ kJ/kg of fuel.}$$

Where,

$\frac{CO \times C}{CO_2 + CO}$ = Mass of carbon burnt to CO, and

23680 = Heat loss due to incomplete combustion of 1 kg of carbon.

e. **Heat Lost due to Unburnt Fuel :**

$$Q_5 = m_{f1} \times CV$$

Where,

m_{f1} = Mass of unburnt fuel per kg of fuel, and
 CV = Calorific value of fuel.

f. Convection and Radiation Losses :

$$Q_6 = Q - (Q_1 + Q_2 + Q_3 + Q_4 + Q_5)$$

Where,

$$Q = m_f \times CV$$

= Heat released per kg of fuel

Que 3.15. Determine equivalent evaporation/kg of fuel and boiler efficiency of a boiler having steam generation at 3 MPa, 350 °C at a rate of 4×10^4 kg/hr. Feed water enters economizer at 100 °C and during one hour test 5×10^3 kg fuel of CV = 3.5×10^4 kJ/kg

is consumed.

AKTU 2014-15, Marks 10

Answer

Given : Rate of steam generated = 4×10^4 kg/hr, $p = 3 \text{ MPa} = 30 \text{ bar}$
 Amount of coal burnt = 5000 kg/h, CV = 3.5×10^4 kJ/kg, Feed water temperature, $T = 100^\circ\text{C}$

To Find : i. Equivalent evaporation. ii. Boiler efficiency.

1. From steam table,

$$h_{f1} = 418.7 \text{ kJ/kg at } 25^\circ\text{C}$$

and

$$h = 3117.5 \text{ kJ/kg at } 30 \text{ bar and } 350^\circ\text{C}$$

2. Equivalent evaporation,
- $m_e = \frac{m_a(h - h_{f1})}{2257}$

$$= \frac{8(3117.5 - 418.7)}{2257}$$

$$\left[\because m_a = \frac{4 \times 10^4}{5 \times 10^3} = 8 \text{ kg of steam/kg of coal} \right]$$

$$= 9.56 \text{ kg of steam/kg of coal}$$

3. Boiler efficiency,
- $\eta_{\text{boiler}} = \frac{m_a(h - h_{f1})}{CV}$

$$= \frac{8(3117.5 - 418.7)}{3.5 \times 10^4} = 0.6168 = 61.68 \%$$

Que 3.16. A boiler generates 7.5 kg of steam per kg of coal burnt at a pressure of 11 bar, from feed water having a temperature of 70 °C. The efficiency of boiler is 75 % and factor of evaporation 1.15, specific heat of steam at constant pressure is 2.3 kJ/kgK. Calculate :

- i. Degree of superheat and temperature of steam generated,
- ii. Calorific value of coal in kJ/kg, and
- iii. Equivalent evaporation in kg of steam per kg of coal.

AKTU 2015-16, 2018-19; Marks 10

Answer

Given : $m_a = 7.5$ kg, $p = 11$ bar, Temperature of feed water = 70°C
 Efficiency of boiler = 75 %, $F_e = 1.15$, $C_{ps} = 2.3$ kJ/kg K

1. At 11 bar from steam table :

$$h_f = 781.1 \text{ kJ/kg,}$$

$$h_{fg} = 1998.5 \text{ kJ/kg,}$$

$$T_s = 184.1^\circ\text{C} = 273 + 184.1 = 457.1 \text{ K}$$

2. Factor of evaporation, $F_e = \frac{[h_f + h_{fg} + C_{ps}(T_{\text{sup}} - T_s)] - h_{f1}}{2257}$

$$\begin{aligned} 1.15 &= \frac{[781.1 + 1998.5 + 2.3(T_{\text{sup}} - 457.1) - 1 \times 4.18 \times (70 - 0)]}{2257} \\ &= \frac{2779.6 + 2.3(T_{\text{sup}} - 457.1) - 292.6}{2257} \\ &= \frac{2487 + 2.3(T_{\text{sup}} - 457.1)}{2257} \end{aligned}$$

$$(T_{\text{sup}} - 457.1) = (1.15 \times 2257 - 2487)/2.3 = 47.2$$

$$\begin{aligned} T_{\text{sup}} &= 504.3 \text{ K} = 504.3 - 273 \\ &= 231.3^\circ\text{C} \end{aligned}$$

3. Degree of superheat = $(T_{\text{sup}} - T_s) = 231.3 - 184.1 = 47.2^\circ\text{C}$.

4. Boiler efficiency = $\frac{m_a(h - h_{f1})}{C}$

$$0.75 = \frac{m_a[h_f + h_{fg} + C_{ps}(T_{\text{sup}} - T_s)] - h_{f1}}{C}$$

$$0.75 = \frac{7.5 \{ [781.1 + 1998.5 + 2.3(504.3 - 457.1) - 1 \times 4.18 \times (70 - 0)] \}}{C}$$

$$= \frac{7.5(2888.16 - 292.6)}{C} = \frac{19466.7}{C}$$

$$C = \frac{19466.7}{0.75} = 25955.6 \text{ kJ/kg}$$

i.e., Calorific value of coal = 25955.6 kJ/kg

5. The equivalent evaporation m_e is given as,

$$m_e = \frac{m_a (h - h_{f1})}{2257} = \frac{7.5 (2888.16 - 292.6)}{2257}$$

$$= 8.625 \text{ kg}$$

Que 3.17. A boiler which was originally designed to use coal as the fuel is converted into oil fired boiler. The details are : Equivalent evaporation from and at 100°C using coal = 8.5 kg/kg of coal. Equivalent evaporation from and at 100°C using oil = 14.5 kg/kg of oil. CV of oil = 42000 kJ/kg . Assuming thermal efficiency of the boiler to be same before and after conversion, find (i) Calorific value of coal, (ii) Thermal efficiency of the boiler, (iii) Mass of oil consumed equivalent to 1000 kg of coal burnt.

AKTU 2017-18, Marks 10

Answer

Given : $(m_e)_c = 8.5 \text{ kg/kg}$ of coal, $(m_e)_o = 14.5 \text{ kg/kg}$ of coal,
Specific gravity of oil = 0.8 , $(CV)_o = 42000 \text{ kJ/kg}$, $m_c = 1000 \text{ kg}$

1. The thermal efficiency of boiler can be written as :

For oil, $\eta = \frac{(m_e)_o}{(CV)_o} \times 2257 \quad \dots(3.17.1)$

For coal, $\eta = \frac{(m_e)_c}{(CV)_c} \times 2257 \quad \dots(3.17.2)$

2. Since the thermal efficiency of the boiler is same before and after conversion, we can equate eq. (3.17.1) and eq. (3.17.2),

$$\frac{(m_e)_o \times 2257}{(CV)_o} = \frac{(m_e)_c \times 2257}{(CV)_c}$$

$$\frac{14.5 \times 2257}{42000} = \frac{8.5 \times 2257}{(CV)_c}$$

$\therefore$ Calorific value of coal, $(CV)_c = 24620.7 \text{ kJ/kg}$ of coal

3. Thermal efficiency of the boiler from eq. (3.17.1),

$$\eta = \frac{14.5 \times 2257}{42000} = 0.7792 \text{ or } 77.92 \%$$

4. Heat supplied in oil = Heat supplied in coal

$$m_o (CV)_o = m_c (CV)_c$$

$$m_o \times 42000 = 1000 \times 24620.7$$

$\therefore$ Mass of oil consumed $m_o = 586.207 \text{ kg}$

PART-6*Classification of Condenser, Air Leakage.***Questions-Answers****Long Answer Type and Medium Answer Type Questions**

Que 3.18. What is the function of condenser? Classify and explain barometric jet condenser with neat sketch.

AKTU 2015-16, Marks 10

Answer**A. Function of Condenser :**

1. Condenser is a device which is used to condense vapour into liquid state at a pressure below atmospheric pressure.
2. It converts the turbine exhaust steam into pure water.

B. Classification of Condenser :**a. Jet Condenser :**

1. Low level jet condenser,
 - i. Parallel flow type
 - ii. Counter flow type
2. High level jet condenser, and
3. Ejector jet condenser.

b. Surface Condenser :

1. Central flow type,
2. Down flow type, and
3. Evaporative flow type.

C. Barometric Jet Condenser :

1. It is also known as high level jet condenser. This barometric jet condenser (shown in Fig. 3.18.1) is similar to low level jet condenser except the column of water in tail pipe.

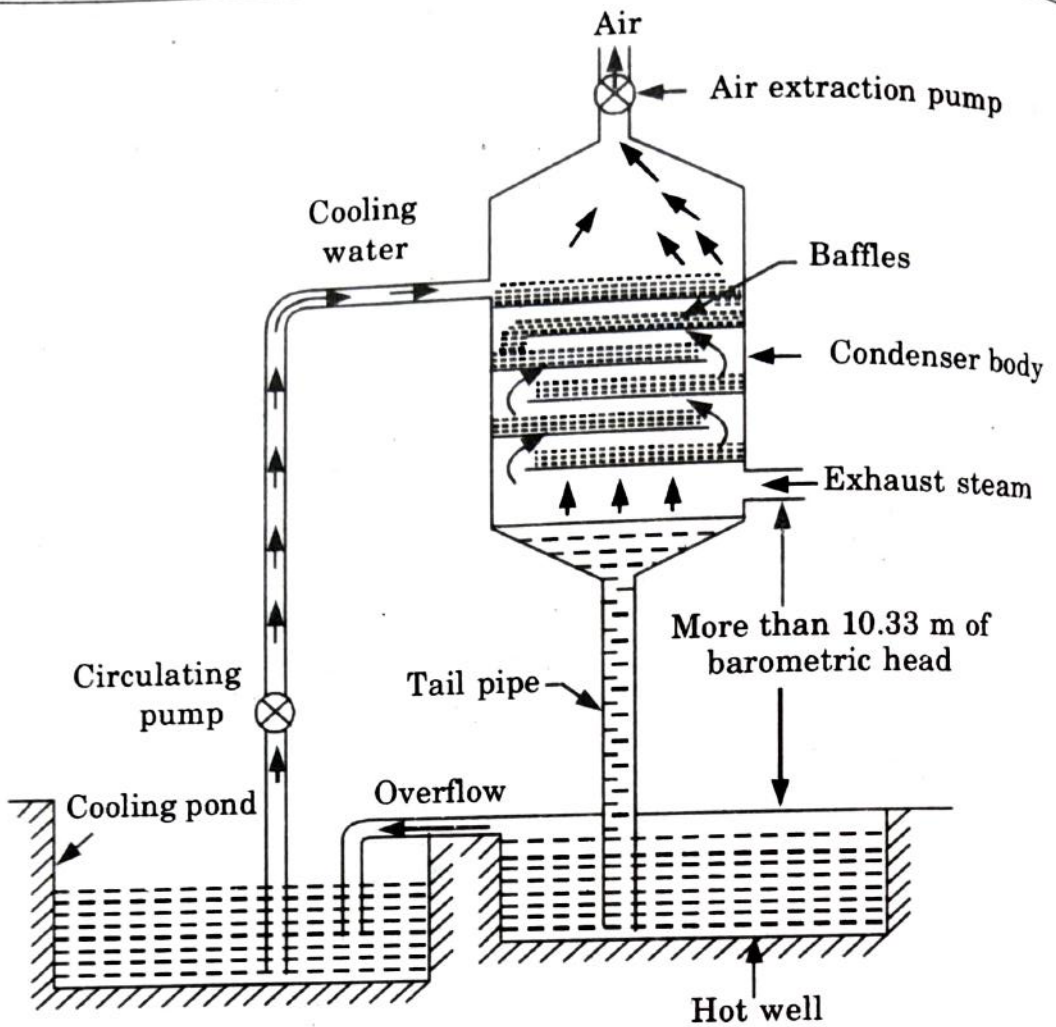


Fig. 3.18.1. Barometric jet condenser.

2. A long tail pipe more than 10.33 m in length is attached to bottom of condenser. This allows the condensate and the coolant to be discharged from the condenser under gravity action.
3. The actual steam jet refrigeration system employs a barometric condenser which is nothing but a direct contact heat exchanger with counter flow heat transfer.
4. The main condensing part is kept at such a height that the inside pressure is equal to the steam pressure corresponding to ambient temperature.
5. As the air and water vapour move up, they come in direct contact with the trickling water droplets. This causes condensation of the vapour while air moves up until air and vapour is sucked by the first stage ejector.
6. The discharge from the first ejector enters the intermediate condenser where the vapour is, further, condensed and the rest amount of air-water vapour enters the third stage. In this stage almost all vapour gets condensed leaving a negligible amount associated with air which is discharged into atmosphere.

Que 3.19. Discuss the causes of air leakage and its effect on condenser.

AKTU 2018-19, Marks 10

Answer

A. Causes of Air Leakage :

1. Leakage through packing glands and joints.
2. Leakage through condenser accessories such as atmospheric relief valve, etc.
3. Air associated with exhaust steam results in air leakage.
4. In case of jet condenser, dissolved air in the cooling water also results in leakage.

B. Effect of Air Leakage on Condenser :

1. Air leakage causes the reduction in work done per kg of steam as it increases the back pressure.
2. Due to air pressure, partial pressure of steam lowers which results in increased quantity of water required for condensation.
3. Air leakage leads to requirement of more quantity of cooling water.
4. Air leakage reduces the condenser efficiency and auxiliary devices such as reciprocating pump, rotary pump, steam ejector or air pumps etc.
5. Presence of air increases corrosive action due to presence of large quantity of oxygen.

PART-7

Condenser Performance Parameters.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 3.20. Write down the condenser performance parameters.

Answer

Condenser performance parameters are as follows :

- a. **Vacuum Efficiency :** It is defined as the ratio of the actual vacuum to the maximum obtainable vacuum.

$$\text{Vacuum efficiency} = \frac{\text{Actual vacuum}}{\text{Maximum obtainable vacuum}}$$

Actual vacuum

$$= \frac{\text{Barometer pressure} - \text{Absolute pressure of steam}}{\text{Barometer pressure}}$$

- b. **Condenser Efficiency** : It is defined as the ratio of the difference between the outlet and inlet temperatures of cooling water to the difference between the temperature corresponding to the vacuum in the condenser and inlet temperature of cooling water.

Condenser efficiency

$$= \frac{\text{Rise in temperature of cooling water}}{\left[\begin{array}{c} \text{Temperature corresponding to} \\ \text{vacuum in condenser} \end{array} \right] - \left[\begin{array}{c} \text{Inlet temperature of} \\ \text{cooling water} \end{array} \right]}$$

Que 3.21.

Condenser vacuum of a surface condenser is 70 cm of Hg, barometric reading is 76.5 cm of Hg. Mean condenser temperature = 35 °C, hot well temperature = 28 °C, condensate collected = 1800 kg/hr, cooling water inlet temperature = 12 °C, cooling water outlet temperature = 27 °C. Calculate : (i) vacuum efficiency,

(ii) condenser efficiency.

AKTU 2017-18, Marks 07

Answer

Given : Condenser vacuum = 70 cm of Hg,

Barometric reading = 76.5 cm of Hg, $T_{ci} = 12^\circ\text{C}$, $T_{co} = 27^\circ\text{C}$,

Condensate collected = 1800 kg/hr, Hot well temperature = 28 °C,

Mean condenser temperature = 35 °C

Data Assumed : $\rho_{Hg} = 0.0135951$

1. Barometric pressure,

$$\begin{aligned} P_b &= \rho_{Hg} H = 76.5 \times 10^{-2} \times 0.0135951 \times 10^6 \times 9.81 \\ &= 102026.46 \text{ N/m}^2 = 102 \text{ kPa} \end{aligned}$$

$$= 1.02 \text{ bar}$$

2. Absolute pressure of steam in condenser = Saturation pressure corresponding to 35 °C

3. Condenser vacuum pressure

$$= 70 \times 10^{-2} \times 0.0135951 \times 10^6 \times 9.81$$

4. Absolute pressure in condenser,

P_c = Barometric pressure – Condenser vacuum pressure

$$= 1.02 - 0.93357 = 0.08643 \text{ bar}$$

Actual vacuum at steam inlet to condenser

$$\eta_{\text{vacuum}} = \frac{\text{Barometric pressure} - \text{Absolute pressure of steam}}{1.02 - 0.0562} = \frac{0.93357}{1.02 - 0.0562} = 0.9686 = 96.86 \%$$

6. Saturation temperature corresponding to absolute pressure in condenser, $T_{\text{sat}} = 42.8^\circ \text{C}$

7. Condenser efficiency,

$$\begin{aligned} \eta_{\text{cond}} &= \frac{\text{Actual cooling water temperature rise}}{\text{Maximum possible temperature rise}} \\ &= \frac{T_{\text{co}} - T_{\text{ci}}}{T_{\text{sat}} - T_{\text{ci}}} \\ &= \frac{27 - 12}{42.8 - 12} = 0.4870 = 48.7 \% \end{aligned}$$

VERY IMPORTANT QUESTIONS

Following questions are very important. These questions may be asked in your SESSIONALS as well as UNIVERSITY EXAMINATION.

Q.1. What are the essentials of a good boiler ? Distinguish between fire tube and water tube boiler. Give two names of each. Give a neat labelled sketch of a Babcock and Wilcox boiler.

~~Ans.~~ Refer Q. 3.4, Unit-3.

Q.2. Explain the working of water level indicator, safety valves, and fusible plug, feed check valve, pressure gauge, stop valve and blow off cock.

~~Ans.~~ Refer Q. 3.5, Unit-3.

Q.3. What are boilers ? How are they classified ? Differentiate between mountings and accessories.

~~Ans.~~ Refer Q. 3.6, Unit-3.

Q.4. What do you understand by boiler draught ? Calculate condition for maximum discharge.

~~Ans.~~ Refer Q. 3.7, Unit-3.

Nozzles and Steam Turbine

CONTENTS

- Part-1 :** Flow through Convergent and 4-2A to 4-5A
Convergent-Divergent Nozzles,
Variation of Velocity, Area and
Specific Volume
- Part-2 :** Choked Flow 4-6A to 4-7A
- Part-3 :** Throat Area, Nozzle Efficiency 4-7A to 4-9A
Off Design Operation of Nozzle
- Part-4 :** Shock Waves, Stationary 4-9A to 4-13A
Normal Shock Waves, Effect of
Friction on Nozzle, Super Saturated Flow
- Part-5 :** Classification of Steam Turbine, 4-13A to 4-15A
Impulse and Reaction Turbines
- Part-6 :** Staging, Stage and Overall 4-15A to 4-16A
Efficiency
- Part-7 :** Reheat Factor, Bleeding 4-16A to 4-17A
- Part-8 :** Velocity Diagram of Simple 4-17A to 4-32A
and Compound Multistage Impulse
and Reaction Turbines and Related
Calculations, Work Done, Efficiencies
of Reaction, Impulse Reaction Turbines
- Part-9 :** State Point Locus, Losses 4-32A to 4-34A
in Steam Turbines
- Part-10 :** Governing of Turbines, 4-34A to 4-36A
Comparison with Steam Engine

PART-1

*Flow through Convergent and Convergent-Divergent Nozzles,
Variation of Velocity, Area and Specific Volume.*

CONCEPT OUTLINE

Coefficient of Velocity : It is defined as the ratio of the actual exit velocity to the exit velocity when flow is isentropic between the same pressures.

$$\text{Coefficient of velocity} = \frac{C_{2'}}{C_2} = \sqrt{\eta_{\text{nozzle}}}$$

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 4.1. Define convergent and convergent-divergent nozzle.

Answer**A. Convergent Nozzle :**

1. The cross-sectional area of this nozzle decreases from inlet to outlet portion.
2. The purpose of this nozzle is to convert the internal energy of the fluid into the kinetic form.

B. Convergent-Divergent Nozzle :

1. Fig. 4.1.1 shows a convergent-divergent nozzle. It has a varying cross-section passage which firstly decreases up to a fixed portion and then increases up to outlet area.

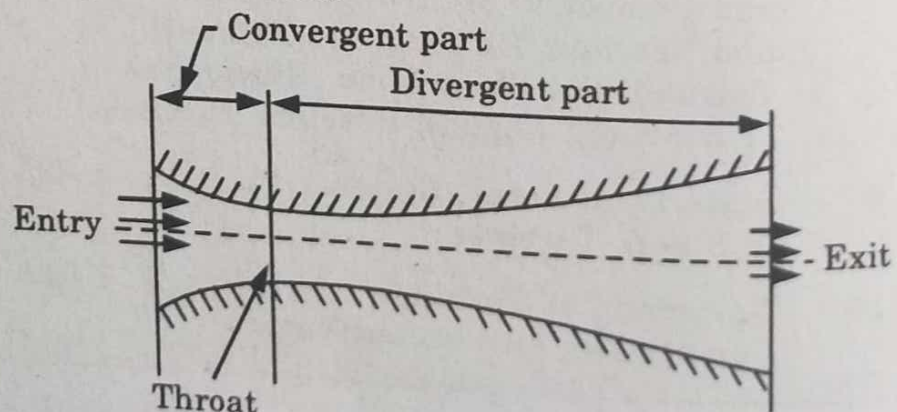


Fig. 4.1.1. C

2. The minimum cross-section area present in nozzle is called throat. The divergent section acts as an accelerator for supersonic flow.

Que 4.2. Define critical pressure ratio for nozzle of the steam turbine. Obtain analytically its value in terms of the index of expansion.

AKTU 2015-16, Marks 10

Answer

A. Critical Pressure Ratio : It is defined as the ratio of throat pressure to inlet pressure.

B. Derivation :

1. Let,

p_1 = Initial pressure of steam,

v_1 = Initial specific volume of steam at pressure p_1 (m^3/kg),

p_2 = Pressure of steam at throat,

v_2 = Specific volume of steam at pressure p_2 (m^3/kg),

A = Throat area, and

C = Velocity of steam (m/s).

2. Let steam follows the equation $pv^n = \text{constant}$ for flow through nozzle. Where,

n = Isentropic or process index of expansion,

= 1.135 for saturated steam,

= 1.3 for superheated steam, or

= $1.035 + 0.1x$, for wet steam.

Where,

x = Initial dryness fraction of steam.

3. Work done per kg of steam during the cycle (Rankine cycle)

$$= \frac{n}{n-1} (p_1 v_1 - p_2 v_2)$$

4. Gain in kinetic energy = Adiabatic heat drop
= Work done during Rankine cycle

$$\frac{C^2}{2} = \frac{n}{n-1} (p_1 v_1 - p_2 v_2)$$

$$= \frac{n}{n-1} p_1 v_1 \left(1 - \frac{p_2 v_2}{p_1 v_1} \right)$$

5. As we have, $p_1 v_1^n = p_2 v_2^n$

$$\therefore \frac{v_2}{v_1} = \left(\frac{p_1}{p_2} \right)^{\frac{1}{n}}$$

So

$$\frac{C^2}{2} = \frac{n}{n-1} p_1 v_1 \left[1 - \left(\frac{p_2}{p_1} \right) \left(\frac{p_2}{p_1} \right)^{\frac{-1}{n}} \right]$$

$$C^2 = \frac{2n}{n-1} p_1 v_1 \left[1 - \left(\frac{p_2}{p_1} \right)^{1-\frac{1}{n}} \right]$$

$$C = \sqrt{2 \left(\frac{n}{n-1} \right) p_1 v_1 \left[1 - \left(\frac{p_2}{p_1} \right)^{1-\frac{1}{n}} \right]}$$

6. Let, m = Mass of steam discharged (in kg/s).

Then, $m = \frac{AC}{v_2}$

$$m = \frac{AC}{v_1 \left(\frac{p_1}{p_2} \right)^{\frac{1}{n}}} \quad \left\{ \because v_2 = v_1 \left(\frac{p_1}{p_2} \right)^{\frac{1}{n}} \right\}$$

$$m = \frac{A}{v_1 \left(\frac{p_1}{p_2} \right)^{\frac{1}{n}}} \left[\frac{2n}{n-1} p_1 v_1 \left\{ 1 - \left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} \right\} \right]^{1/2}$$

$$m = \frac{A}{v_1} \left[2 \left(\frac{n}{n-1} \right) p_1 v_1 \left\{ \left(\frac{p_2}{p_1} \right)^{\frac{2}{n}} - \left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} \left(\frac{p_2}{p_1} \right)^{\frac{2}{n}} \right\} \right]^{1/2}$$

$$m = \frac{A}{v_1} \left[2 \left(\frac{n}{n-1} \right) p_1 v_1 \left\{ \left(\frac{p_2}{p_1} \right)^{\frac{2}{n}} - \left(\frac{p_2}{p_1} \right)^{\frac{n+1}{n}} \right\} \right]^{1/2} \dots (4.2.1)$$

From eq. (4.2.1) it is clear that maximum discharge depends upon the critical pressure ratio $\frac{p_2}{p_1} = r$ (let).

7. Now, from eq. (4.2.1),

$$m^2 = \frac{A^2}{v_1^2} \left[2 \left(\frac{n}{n-1} \right) p_1 v_1 \left\{ r^{\frac{2}{n}} - r^{\frac{n+1}{n}} \right\} \right]$$

$$\frac{dm}{dr} = \frac{A^2}{v_1^2} \left[2 \left(\frac{n}{n-1} \right) p_1 v_1 \left\{ \frac{2}{n} r^{\frac{2}{n}-1} - \left(\frac{n+1}{n} \right) r^{\frac{1}{n}} \right\} \right]$$

8. For maximum discharge,

$$\frac{dm}{dr} = 0$$

$$0 = \frac{A^2}{v_1^2} \left[2 \left(\frac{n}{n-1} \right) p_1 v_1 \left\{ \frac{2}{n} r^{\frac{2}{n}-1} - \left(\frac{n+1}{n} \right) r^{\frac{1}{n}} \right\} \right]$$

$$\frac{2}{n} r^{\frac{2}{n}-1} - \left(\frac{n+1}{n} \right) r^{\frac{1}{n}} = 0$$

$$\frac{2}{n} r^{\frac{2}{n}-1} = \frac{n+1}{n} r^{\frac{1}{n}}$$

$$r^{\frac{2}{n}-1-\frac{1}{n}} = \frac{n+1}{2}$$

$$\left(\frac{p_2}{p_1} \right)^{\frac{1-n}{n}} = \frac{n+1}{2}$$

$$\frac{p_2}{p_1} = \left(\frac{2}{n+1} \right)^{\frac{n}{n-1}}$$

$$\frac{\text{Throat pressure}}{\text{Inlet (or intake) pressure}} = \left(\frac{2}{n+1} \right)^{\frac{n}{n-1}}$$

Que 4.3. Define the steam nozzle. Also derive the expressions for velocity of steam and discharge through steam nozzle.

AKTU 2017-18, Marks 10

Answer

A. Steam Nozzle: It is defined as a passage of varying cross-section through which heat energy of steam is converted into kinetic energy.

B. Expression for Velocity of Steam through Steam Nozzle :

- Let
 h_1 = Enthalpy of steam entering the nozzle,
 h_2 = Enthalpy of steam at section considered, and
 h_d = Heat drop during expansion of steam in the nozzle.

$$= (h_1 - h_2).$$

- Considering 1 kg of steam and flow to be frictionless adiabatic, we have

$$\frac{C^2}{2} = h_d$$

$$C = \sqrt{2 \times 1000 h_d} = 44.72 \sqrt{h_d}$$

- In practice, there is loss due to friction in the nozzle and its value varies from 10 to 15 percent of total heat drop. Due to this, total heat drop is minimized.

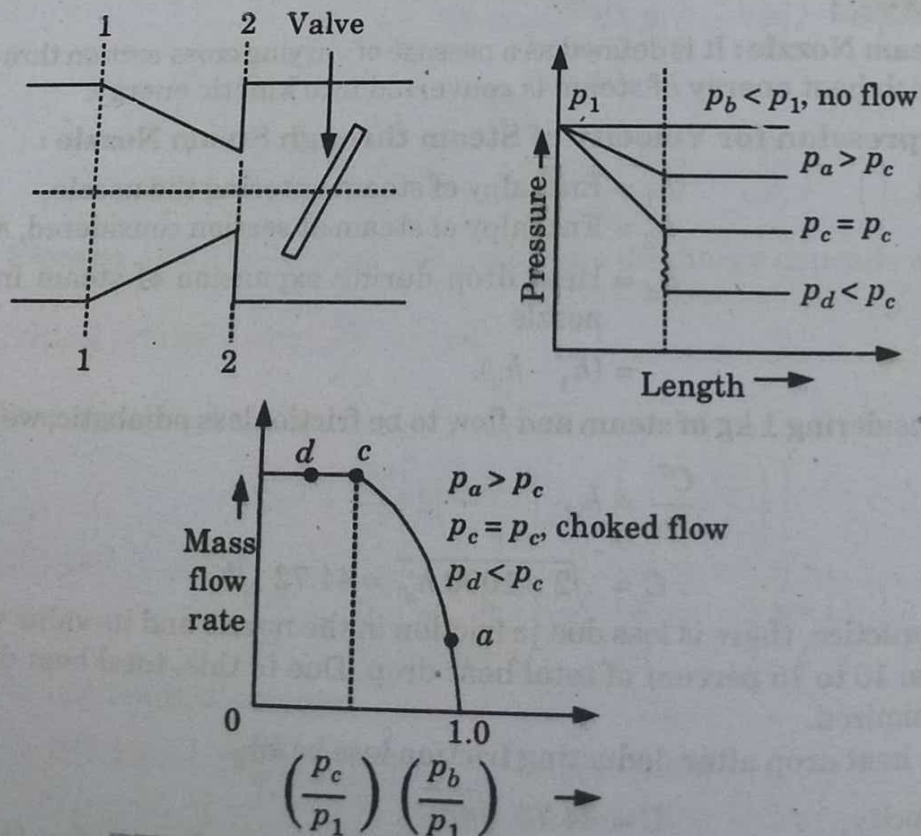
- Let heat drop after deducting friction loss be kh_d .

$$\text{Velocity, } C = 44.75 \sqrt{kh_d}$$

C. Expression for Discharge through Nozzle : Refer Q. 4.2,

PART-2*Choked Flow.***Questions-Answers****Long Answer Type and Medium Answer Type Questions****Que 4.4.** What do you mean by choked flow ?**Answer**

1. The flow condition in which a nozzle operating with maximum mass flow rate is known as choked flow.
2. Choking of a fluid in nozzle is the condition of reduction in fluid pressure.
3. Let us consider a converging nozzle shown in Fig. 4.4.1. A valve is provided at exit of nozzle for regulating the back pressure at section 2-2.
4. Let the back pressure is p_b and p_1 is the pressure at the inlet.

**Fig. 4.4.1.** Flow through a convergent nozzle.

- i. When $p_b = p_1$,
 $\Rightarrow$ No flow through the nozzle.
- ii. When $p_b < p_1$,
 $\Rightarrow$ Mass flow rate starts increasing.
- iii. When $\frac{p_b}{p_1} = \text{Critical pressure ratio, } p_c = \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}$
 $\Rightarrow$ Mass flow through nozzle is maximum and this flow is known as choked flow or critical flow.

PART-3

Throat Area, Nozzle Efficiency, off Design Operation of Nozzle.

CONCEPT OUTLINE

Throat : The section of minimum cross-sectional area is called throat. Velocity at throat of nozzle operating at designed pressure ratio is the velocity of sound.

Off Design Operation of Nozzle : Design operation of nozzle refers to the nozzle operating with pressure ratio equal to critical pressure ratio and maximum discharge rate per unit area then nozzle is said to be operating under design conditions. If the nozzle does not operate under design conditions then it is called off design operation of nozzle.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 4.5. Define the term nozzle efficiency.

Answer

1. It is defined as the ratio of actual enthalpy drop to the isentropic enthalpy drop between the same pressure.

$$\eta_{\text{nozzle}} = \frac{h_1 - h_2}{h_1 - h_2'}$$

2. If the actual velocity at exit from the nozzle is C_2 , and the velocity at exit when the flow is isentropic is C_2' then,

$$\eta_{\text{nozzle}} = \frac{C_2'^2 - C_1^2}{C_2^2 - C_1^2}$$

3. As the inlet velocity C_1 is negligible then,

$$\eta_{\text{nozzle}} = \frac{C_2'^2}{C_2^2}$$

Que 4.6. A convergent divergent nozzle expands air at 6.89 bar and 427 °C into a space at 1 bar. The throat area is 650 mm² and exit area is 975 mm². The exit velocity is found to be 680 m/s when the inlet velocity is negligible. Assuming negligible friction. Calculate:

- Mass flow through the nozzle.
- Nozzle efficiency and coefficient of velocity.

AKTU 2018-19, Marks 07

Answer

Given : $p_1 = 6.89$ bar, $p_2 = 1$ bar, $T_1 = 427$ °C = 700 K,
 $A_1 = 650$ mm², $C_2' = 680$ m/s, For air, $\gamma = 1.4$
 Data Assumed : $n = 1.3$

- We know that, $\frac{p_c}{p_1} = \left(\frac{2}{n+1}\right)^{\frac{n}{n+1}} = \left(\frac{2}{1.3+1}\right)^{\frac{1.3}{1.3+1}} = 0.545$
 $p_c = 0.545 \times 6.89 = 3.76$ bar
 $p_c > p_2$ ($\therefore$ Nozzle is choked)
- Also, $\frac{T_c}{T_1} = \frac{2}{n+1} = \frac{2}{1.3+1} = 0.869$
 $T_c = 0.869 \times 700 = 608.3$ K
- We know that, $C_1 = C_c = \sqrt{nRT_c} = \sqrt{1.3 \times 287 \times 608.3} = 476.39$ m/s
- Also, $v_1 = v_c = \frac{RT_c}{p_c} = \frac{287 \times 608.3}{3.76 \times 10^5} = 0.46$ m³/kg
- Mass flow rate, $m = \frac{C_1 A_1}{v_1} = \frac{476.39 \times 650 \times 10^{-6}}{0.46} = 0.673$ kg/s
- Also, $\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{1}{6.89}\right)^{0.4/1.4} = 0.576$
 $T_2 = 0.576 \times 700 = 403.28$ K
- We know that, $C_2 = \sqrt{2C_p(T_1 - T_2)}$
 $= \sqrt{2 \times 1.005 \times 10^3 (700 - 403.28)}$
 $= 772.27$ m/s
- Nozzle efficiency, $\eta_{\text{nozzle}} = \left(\frac{C_2'}{C_2}\right)^2 = \left(\frac{680}{772.27}\right)^2 = 0.775 = 77.5\%$

9. Coefficient of velocity = $\frac{C_2'}{C_2} = \frac{680}{772.27} = 0.88$

PART-4

Shock Waves, Stationary Normal Shock Waves, Effect of Friction on Nozzle, Supersaturated Flow.

CONCEPT OUTLINE

Shock Wave : The waves occurring due to abrupt changes in fluid properties that occur in a very thin section of a converging diverging nozzle under supersonic flow conditions are known as shock waves.

Normal Shock Wave : The shock waves that occur in a plane normal to the direction of flow are known as normal shock waves. The flow process through the shock wave is highly irreversible.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 4.7. What do you mean by choked flow ? Explain and write effect of friction on nozzle.

AKTU 2016-17, Marks 10

Answer

A. Choked Flow : Refer Q. 4.4, Page 4-6A, Unit-4.

B. Effect of Friction on Nozzle :

1. The actual expansion is not isentropic hence enthalpy drop is reduced.
2. The final dryness fraction of steam is increased due to kinetic energy of steam gets converted into heat and this heat is absorbed by steam.
3. The steam becomes drier as compared to ideal condition so its specific volume increases. It means the effect of friction improves the quality of steam.
4. Friction tends to superheat the steam and decrease the velocity of steam.

Que 4.8. Write short note on supersaturated flow through the nozzle.

4-10 A (ME-Sem-4)

Answer

1. The converging part of nozzle is short and steam velocity is high so steam molecules do not have sufficient time to collect and form droplets thus normal condensation does not take place.
2. This type of rapid expansion is said to be metastable and produces a supersaturated state.
3. In this expansion or state of supersaturation the steam is undercooled to a temperature less than that corresponding to its pressure which results in increased density of steam and weight of discharge.
4. The phenomenon of supersaturation in steam nozzles is called as supersaturated flow or metastable flow in steam nozzle.

Que 4.9. In a steam nozzle steam expands from 16 bar to 5 bar with initial temperature of 300 °C and mass flow of 1 kg/s. Determine the throat and exit areas considering

- i. Expansion to be frictionless, and
- ii. Friction loss of 10 % throughout the nozzle.

AKTU 2016-17, Marks 10

Answer

Given: $p_1 = 16$ bar, $T_1 = 300$ °C, $p_3 = 5$ bar, $m = 1$ kg/s

1. From steam table
At 16 bar and 300 °C:

$$h_1 = 3034.8 \text{ kJ/kg}, s_1 = 6.8844 \text{ kJ/kg-K}$$

$$v_1 = 0.15862 \text{ m}^3/\text{kg}$$
2. Pressure at throat of nozzle, $p_2 = p_1 \left(\frac{2}{n+1} \right)^{n/(n-1)}$

$$= 16 \left(\frac{2}{1.3+1} \right)^{1.3/(1.3-1)} \quad (\because n = 1.3)$$

$$p_2 = 8.73 \text{ bar}$$
3. Enthalpy at throat and exit of nozzle can be looked from steam table as,

$$h_2 = 2891.39 \text{ kJ/kg}, h_3 = 2777.0 \text{ kJ/kg},$$

$$v_2 = 0.2559 \text{ m}^3/\text{kg}, v_3 = 0.3882 \text{ m}^3/\text{kg}$$
4. Heat drop up to throat section $\Delta Q_{12} = h_1 - h_2 = 3034.8 - 2891.39$

$$= 143.41 \text{ kJ/kg}$$

Velocity at throat, $C_2 = \sqrt{2(h_1 - h_2) \times 1000} = 535.56 \text{ m/s}$
5. Heat drop from throat to exit, $\Delta Q_{23} = h_2 - h_3 = 2891.39 - 2777.0$

$$\Delta Q_{23} = 114.39 \text{ kJ/kg}$$

Velocity at exit, $C_3 = \sqrt{2(h_2 - h_3) \times 1000 + C_2^2}$

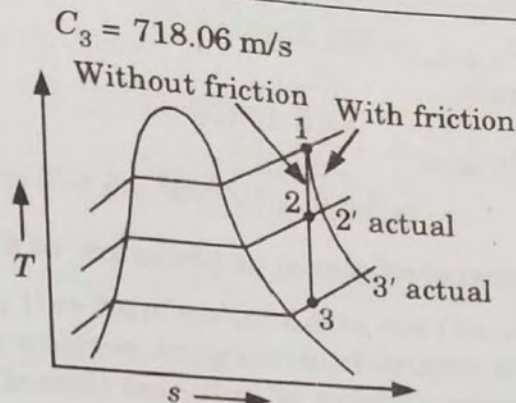


Fig. 4.9.1.

6. Throat area, $A_2 = \frac{m_2 v_2}{C_2} = \frac{1 \times 0.2559}{535.56} = 0.000478 \text{ m}^2$

Exit area, $A_3 = \frac{m_3 v_3}{C_3} = \frac{1 \times 0.3882}{718.06} = 0.000541 \text{ m}^2$

7. Due to frictional heat loss actual heat drop shall get reduced.
Actual heat drop upto throat,

$$\Delta Q'_{12} = 0.9 \Delta Q_{12} = 0.9 \times 143.41$$

$$\Delta Q'_{12} = 129.07 \text{ kJ/kg}$$

Thus, enthalpy at throat, $h_{2, \text{actual}} = 2905.73 \text{ kJ/kg}$

8. From steam table, $v_{2, \text{actual}} = 0.2598 \text{ m}^3/\text{kg}$ corresponding to the modified state as indicated by enthalpy, $h_{2, \text{actual}}$.

9. This new state at throat shall have temperature of 231.35°C , which can be calculated from known enthalpy $h_{2, \text{actual}}$ at respective pressure.

10. Actual velocity at throat,

$$\begin{aligned} C_{2, \text{actual}} &= \sqrt{2 \times (h_1 - h_{2, \text{actual}}) \times 10^3} \\ &= \sqrt{2 \times 129.07 \times 10^3} = 508.1 \text{ m/s} \end{aligned}$$

Actual throat area,

$$A_{2, \text{actual}} = \frac{1 \times 0.2598}{508.1} = 5.11 \times 10^{-4} \text{ m}^2 = 5.11 \text{ cm}^2$$

11. Actual heat drop from throat to exit of nozzle,

$$\begin{aligned} \Delta Q'_{23} &= 0.9 \Delta Q_{23} = 0.9 \times 114.39 \\ &= 102.95 \text{ kJ/kg} \end{aligned}$$

Thus, enthalpy at exit,

$$\begin{aligned} h_{3, \text{actual}} &= 2905.73 - 102.95 \\ &= 2802.78 \text{ kJ/kg} \end{aligned}$$

12. From steam table, corresponding to modified state as given by $h_{3, \text{actual}}$ the specific volume can be given as,

$$v_{3, \text{actual}} = 0.40023 \text{ m}^3/\text{kg}$$

13. Actual velocity at exit,

$$C_{3, \text{actual}} = \sqrt{(2 \times 102.95 \times 10^3) + (508.1)^2}$$

$$C_{3, \text{actual}} = 681.22 \text{ m/s}$$

Actual area at exit,

$$A_{3, \text{actual}} = \frac{1 \times 0.40023}{681.22} = 5.875 \times 10^{-4} \text{ m}^2 = 5.875 \text{ cm}^2$$

Que 4.10. Dry saturated steam at pressure of 6 bar flows through converdiver nozzle at rate of 4.5 kg/sec and exit pressure as 1.6 bar loss due to friction occurs in divergent section at 12 % as friction drop. Determine cross-section of exit and throat area.

AKTU 2014-15, Marks 10

Answer

Given : Initial condition, $p_1 = 6 \text{ bar}$, $x_1 = 1$, $\dot{m} = 4.5 \text{ kg/s}$

Final condition, $p_3 = 1.6 \text{ bar}$

Friction loss = 12 % of total isentropic enthalpy drop

To Find : Cross-section of exit and throat area.

Data Assumed : $n = 1.135$.

$$1. \text{ Throat pressure, } p_2 = p_1 \left(\frac{2}{n+1} \right)^{\frac{n}{n-1}}$$

$$= 6 \left(\frac{2}{1.135+1} \right)^{\frac{1.135}{(1.135-1)}} = 3.46 \text{ bar}$$

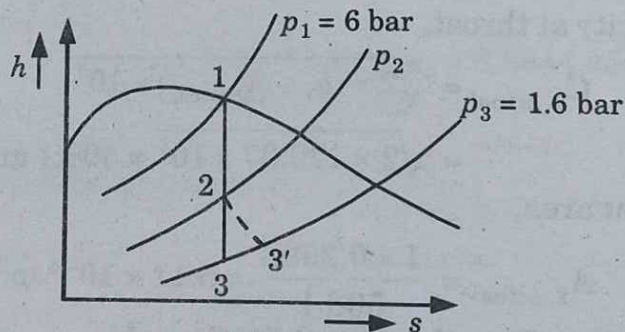


Fig. 4.10.1.

$$2. \text{ At, } p_1 = 6 \text{ bar}$$

$$h_1 = h_g = 2755.5 \text{ kJ/kg}$$

3. From Mollier diagram,

$$\text{Enthalpy drop} = \frac{100}{1.6} \times 2$$

$$h_d = 125 \text{ kJ/kg}$$

$$\left\{ \begin{array}{l} \therefore \text{for } 1.6, h_d = 100 \\ \therefore \text{for } 2.0, h_d = \frac{100}{1.6} \times 2 \end{array} \right\}$$

$$4. \text{ Specific volume, } v_2 = 0.5 + \left(\frac{1.0 - 0.5}{1.7} \right) \times 0.4 \text{ m}^3/\text{kg}$$

5. Velocity of steam at throat, $= 0.62 \text{ m}^3/\text{kg}$
- $$C_2 = 44.72\sqrt{h_d} \text{ m/s}$$
- $$= 44.72\sqrt{125} \text{ m/s}$$
- $$= 499.99 \text{ m/s} \approx 500 \text{ m/s}$$
6. Throat area, $A_2 = \frac{\dot{m} v_2}{C_2} = \frac{4.5 \times 0.62}{500} = 5.58 \times 10^{-3} \text{ m}^2$
7. From Mollier diagram isentropic heat drop from 1-3 is
- $$h_d = \frac{100}{1.6} \times 3.8 = 237.5 \text{ kJ/kg}$$
8. So the exit velocity,
- $$C_3 = 44.72\sqrt{kh_d}$$
- $$\therefore k = 1 - \left(\frac{12}{100}\right) = 0.88$$
- Exit velocity, $C_3 = 44.72\sqrt{0.88 \times 237.5} = 646.51 \text{ m/s}$
9. From Mollier chart specific volume at exit, $v_3 = 1.0 \text{ m}^3/\text{kg}$
- Exit area, $A_3 = \frac{\dot{m} v_3}{C_3} = \frac{4.5 \times 1.0}{646.51} \text{ m}^2 = 6.96 \times 10^{-3} \text{ m}^2$

PART-5

Classification of Steam Turbine, Impulse and Reaction Turbines.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 4.11. Define steam turbine and classify them.

Answer

- A. Steam Turbine :** It is a prime mover in which the potential energy of the steam is transformed into kinetic energy, and later on it is transformed into the mechanical energy of rotation of the turbine shaft.
- B. Classification of Steam Turbine :**
- a. According to Action of Steam :**
1. Impulse turbine, and
 2. Reaction turbine.

4-14 A (ME-Sem-4)

b. According to Number of Pressure Stage :

1. Single stage turbine, and
2. Multistage turbine.

c. According to the Direction of Flow :

1. Axial flow turbine, and
2. Radial flow turbine.

d. According to Number of Cylinder :

1. Single cylinder turbine, and
2. Multi cylinder turbine.

e. According to Method of Governing :

1. Turbine with throttle governing,
2. Turbine with nozzle governing, and
3. Turbine with by-pass governing.

f. According to Steam Condition at Inlet to Turbine :

1. Low pressure turbine,
2. Medium pressure turbine, and
3. High pressure turbine.

Que 4.12. Explain the principle of working of steam impulse turbine.

Answer

1. Steam turbine one set of nozzle followed by the moving blades.
2. As steam flows through the nozzle, expansion of the steam take place and its pressure will fall down.
3. Due to expansion of steam, velocity of jet of steam coming out from the nozzle will increase.
4. High velocity jets of steam impinge upon the blade and get deflected by an angle and finally come out with lower velocity and impress a torque on the blade. Thus, blade of wheel rotates due to the impulsive effect of the jet.

Que 4.13. Write short note on reaction turbine.

Answer

1. In a reaction turbine, forces driving the rotor are achieved by the reaction of an accelerating water flow in the runner while the pressure drops.
2. In reaction turbines torque developed by reacting to the fluid's pressure. The pressure of the fluid changes as it passes through the turbine rotor blades.

3. Pressure drop is usually higher for the fixed blades and greater for the high pressure conditions, where the pressure drop per unit of enthalpy drop is higher at the high pressure.
4. The rotor blades of a reaction turbine are not symmetrical as in the impulse turbine, they are similar to those of the stator but curved in the opposite direction.

PART-6

Staging, Stage and Overall Efficiency.

CONCEPT OUTLINE

Staging : Staging is basically stacking a group of turbines one after the other so that steam gives up only part of its energy at each unit or stage.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 4.14. What are the different types of turbine efficiency? Give their description.

Answer

A. Blade or Diagram Efficiency (η_{bl}) :

1. It is the ratio of work done on the blade per second to the energy entering the blade per second.

$$\begin{aligned}\eta_{bl} &= \frac{\text{Work done on blade / second}}{\text{Energy entering the blade / second}} \\ &= \frac{mU\Delta C_w}{m \frac{C_1^2}{2}} = \frac{2U\Delta C_w}{C_1^2}\end{aligned}$$

Where,

$$U = \text{Linear velocity of steam} = \frac{\pi dN}{60},$$

C_1 = Absolute velocity of steam at inlet to moving blade, and

$\Delta C_w = C_{w1} + C_{w2}$ = Sum of whirl velocities at inlet and outlet.

B. Stage Efficiency :

1. It is the ratio of rate of work done and energy supplied to the stage.
2. Energy supplied to stage = $m(h_0 - h_1)$

Where, h_0 and h_1 are the enthalpies at state 0 and 1.

$$\eta_{\text{stage}} = \frac{\text{Rate of work done}}{\text{Energy supplied to stage}} = \frac{U \Delta C_w}{h_0 - h_1}$$

3. Stage efficiency = Blade efficiency $\times$ Nozzle efficiency.

C. Nozzle Efficiency :

1. It is the ratio of kinetic energy available and the enthalpy change occurring across the nozzle.

$$\eta_{\text{nozzle}} = \frac{m \frac{C_1^2}{2}}{m(h_0 - h_1)} = \frac{C_1^2}{2(h_0 - h_1)}$$

D. Overall Efficiency :

1. It is the ratio of work delivered at turbine shaft to the energy supplied to the stage.

$$\eta_0 = \frac{\text{Work delivered at shaft}}{\text{Energy supplied to stage}}$$

2. Overall efficiency, $\eta_0 = \text{Nozzle efficiency} \times \text{Diagram efficiency} \times \text{Mechanical efficiency}$

PART-7

Reheat Factor, Bleeding.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 4.15. Explain reheat factor.

Answer

1. Consider a four stage turbine for the steam as shown in Fig. 4.15.1. Initial conditions are known at point 1.
2. From Fig. 4.15.1, 1-2 is adiabatic expansion and point 2' is located on same pressure line as point 2.
3. Now again due to adiabatic expansion we obtain point 3. Similarly we obtain the points 4 and 5 after adiabatic expansion from point 3' and 4'.
4. Sum of adiabatic heat drop $(1-2) + (2'-3) + (3'-4) + (4'-5)$ is termed as cumulative heat drop and represented by h_{cum} .

$$h_{\text{cum}} = (h_1 - h_2) + (h_{2'} - h_3) + (h_{3'} - h_4) + (h_{4'} - h_5)$$
5. The adiabatic heat drop from point 1 to point 6 is $(h_1 - h_6)$, if we consider all the stages as one unit.

$$h_{\text{adi}} = h_1 - h_6$$

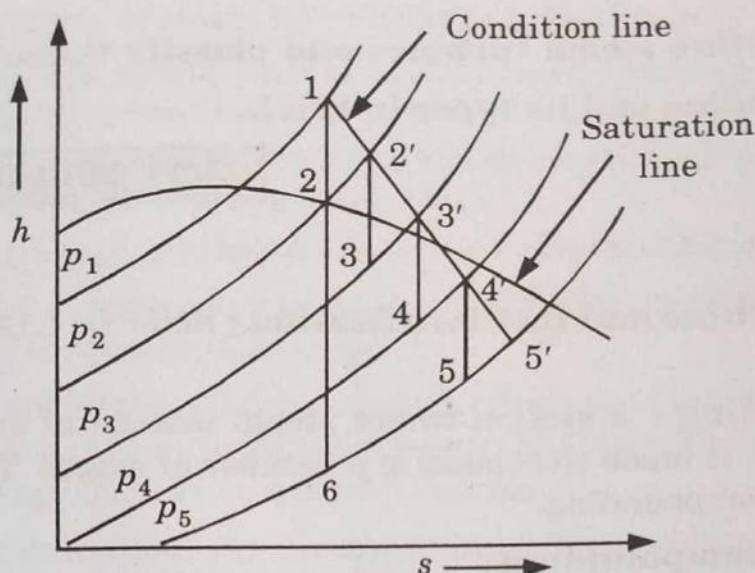


Fig. 4.15.1. *h-s diagram of four stage turbine.*

6. The ratio of cumulative heat drop to adiabatic heat drop is termed as reheat factor.

$$\begin{aligned} \text{Reheat factor (RF)} &= \frac{\text{Cumulative heat drop}}{\text{Adiabatic heat drop}} = \frac{h_{\text{cum}}}{h_{\text{adi}}} \\ &= \frac{(h_1 - h_2) + (h_{2'} - h_3) + (h_{3'} - h_4) + (h_{4'} - h_5)}{(h_1 - h_6)} \end{aligned}$$

Que 4.16. Write a short note on bleeding of steam turbine.

Answer

1. In bleeding process, at certain points, steam is drained out from turbine and is supplied for heating the feed water.
2. A certain amount of steam is drained out from the turbine and circulated around the feed water pipe.
3. Water in feed pipe has temperature lower than the steam. Due to this difference, steam gives its heat to feed water and gets condensed.
4. By this process, process efficiency is increased but at the same time the power developed is decreased.

PART-8

Velocity Diagram of Simple and Compound Multistage Impulse and Reaction Turbines and Related Calculations, Work Done, Efficiencies of Reaction, Impulse Reaction Turbines.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 4.17. Define steam turbines and classify them. Explain the term compounding and its types in brief.

AKTU 2014-15, Marks 10

Answer

A. Steam Turbine and Its Classification : Refer Q. 4.11, Page 4-13A, Unit-4.

B. Compounding : A system where steam instead of expanding in a single stage is made to expand in a number of stages. This method is known as compounding.

C. Types of Compounding :

a. Velocity Compounding or Curtis Compounding :

1. In velocity compounding turbine, steam is expanded in nozzles from the inlet pressure to condenser pressure.

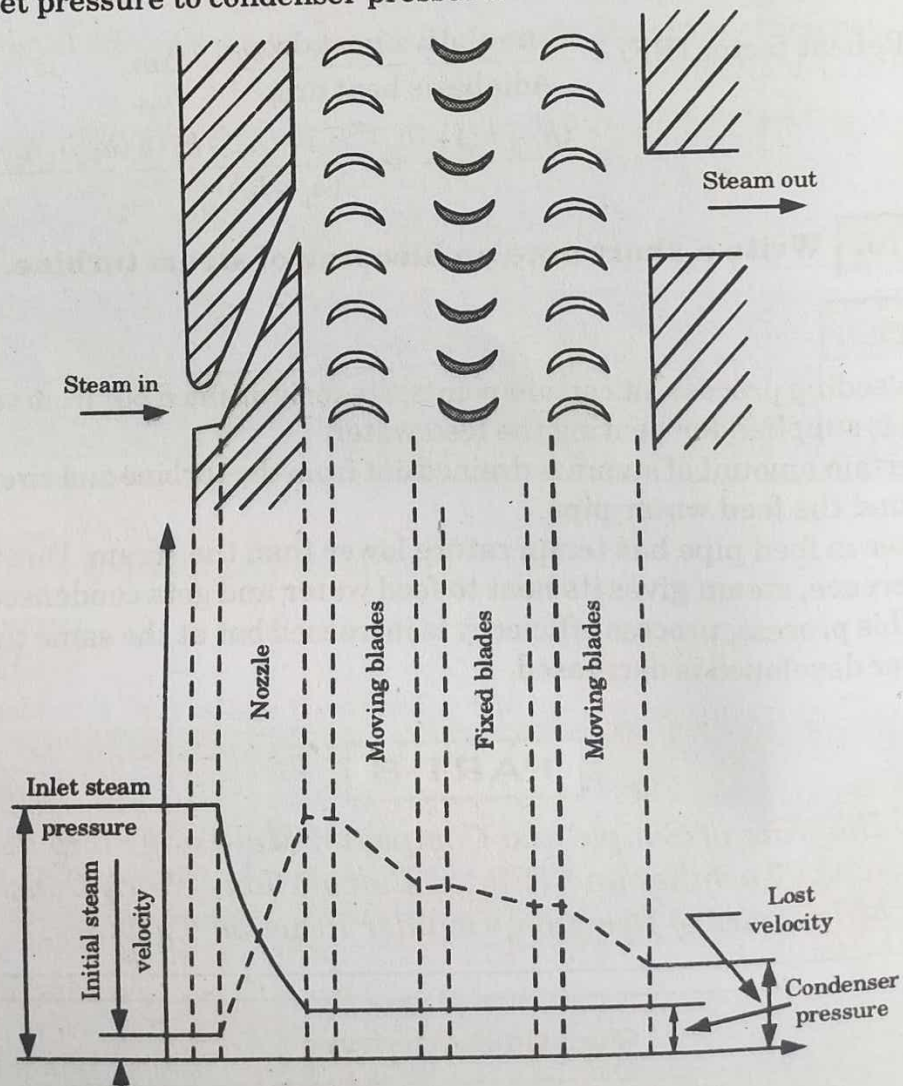


Fig. 4.17.1. Velocity compounding.

2. Due to expansion of steam its velocity or kinetic energy is increased.
3. A portion of this kinetic energy is absorbed by moving blade and the steam is passed to the fixed blade.
4. Function of fixed blade is to redirect the steam without losing its kinetic energy for the next row of moving blade.

b. Pressure Compounding or Rateau Compounding :

1. The pressure compounding or Rateau compounding turbine consists of a number of simple impulse stage.
2. The steam at boiler pressure enters the first set of nozzle and expands partially, this increases the kinetic energy. This kinetic energy is absorbed by the moving blade. This is the first stage.
3. Then steam enters into the nozzle of second stage and expands partially where its velocity increases again and the kinetic energy is again absorbed by the moving blade. This is second stage.
4. After stage two, steam enters the nozzle of third stage and due to expansion, pressure decreases and velocity increases and the kinetic energy thus obtained is absorbed by moving blade. This is third stage.

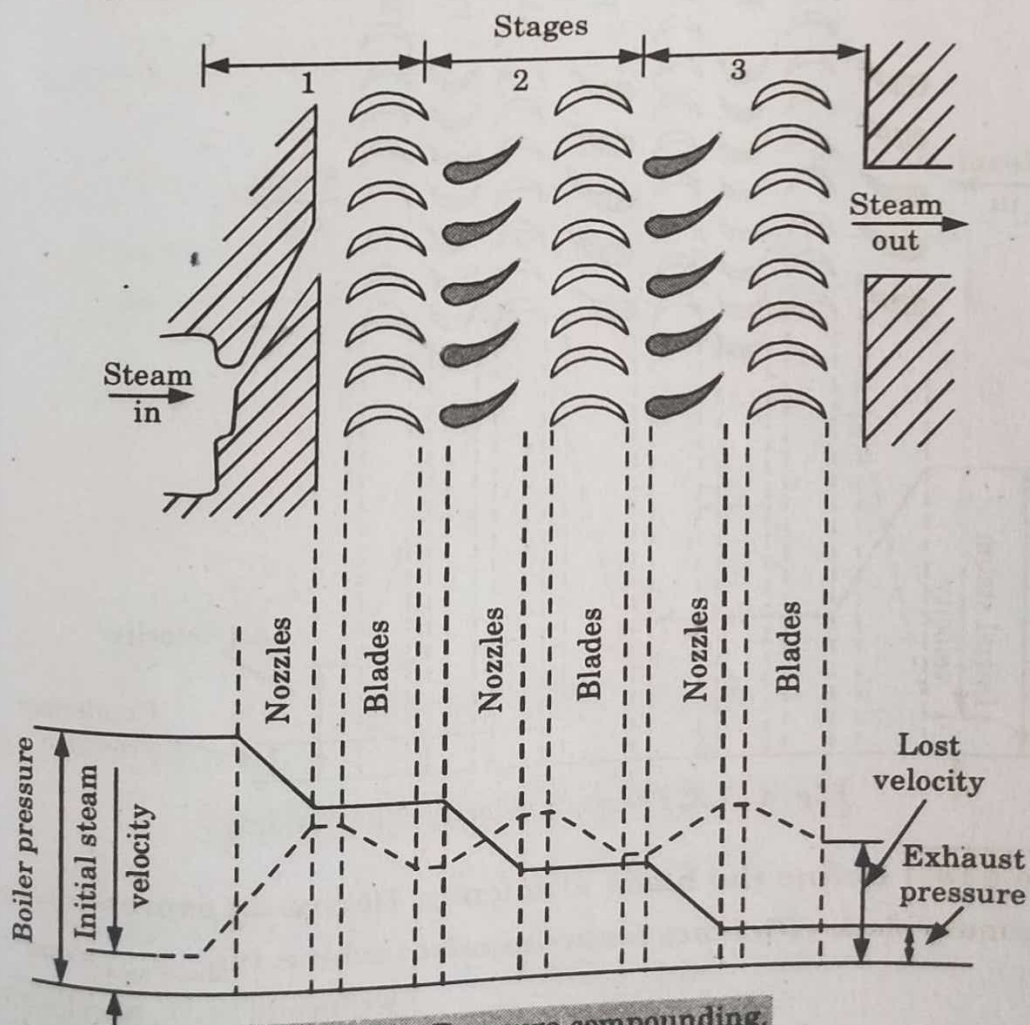


Fig. 4.17.2. Pressure compounding.

c. Pressure Velocity Compounding :

1. In this method, total drop in steam pressure is divided into stages and the velocity obtained in each stage is also compounded.
2. The stage consists of fixed nozzles, moving blades, fixed blades, moving blades in a sequence.
3. The pressure of steam drops only in nozzle and remains constant while travelling over moving blades and fixed blades.
4. The variation of velocity is as follows :
 - i. Velocity of steam increases into nozzle.
 - ii. Velocity of steam decreases into moving blades.
 - iii. Velocity of steam remains constant while flowing on fixed blades.

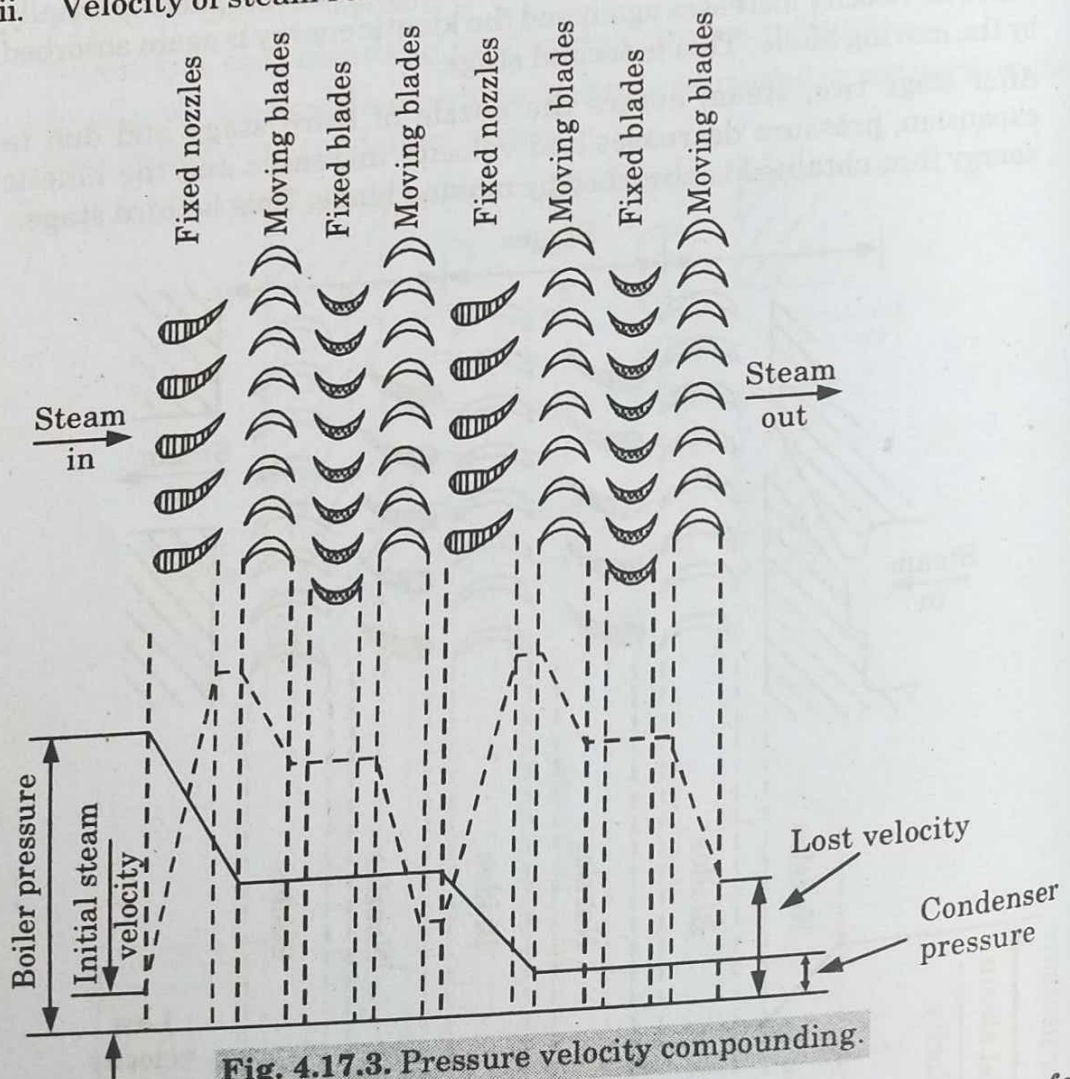


Fig. 4.17.3. Pressure velocity compounding.

Que 4.18. Define the blade efficiency. Derive an expression for maximum blade efficiency for an impulse turbine. $(\eta_{\text{blade}})_{\text{max}} = \cos^2 \alpha$.

AKTU 2017-18, Marks 10

Answer

A. **Blade Efficiency :** Refer Q. 4.14, Page 4-15A, Unit-4.

B. **Expression for Maximum Blade Efficiency :**

1. Blade or diagram efficiency for an impulse turbine is given as,

$$\eta_{bl} = \frac{2C_{bl}(C_{w1} + C_{w0})}{C_1^2}$$

Here,

$$C_w = C_{w1} + C_{w0}$$

So,

$$\eta_{bl} = \frac{2C_{bl}C_w}{C_1^2} \quad \dots(4.18.1)$$

2. From Fig. 4.18.1,

$$\begin{aligned} C_w &= PQ = MP + MQ \\ &= C_{r1} \cos \theta + C_{r0} \cos \phi \\ &= C_{r1} \cos \theta \left(1 + \frac{C_{r0} \cos \phi}{C_{r1} \cos \theta} \right) \\ &= C_{r1} \cos \theta (1 + KZ) \end{aligned}$$

Where,

$$Z = \frac{\cos \phi}{\cos \theta} \text{ and}$$

$$K = \frac{C_{r0}}{C_{r1}} \quad \text{(Blade friction factor)}$$

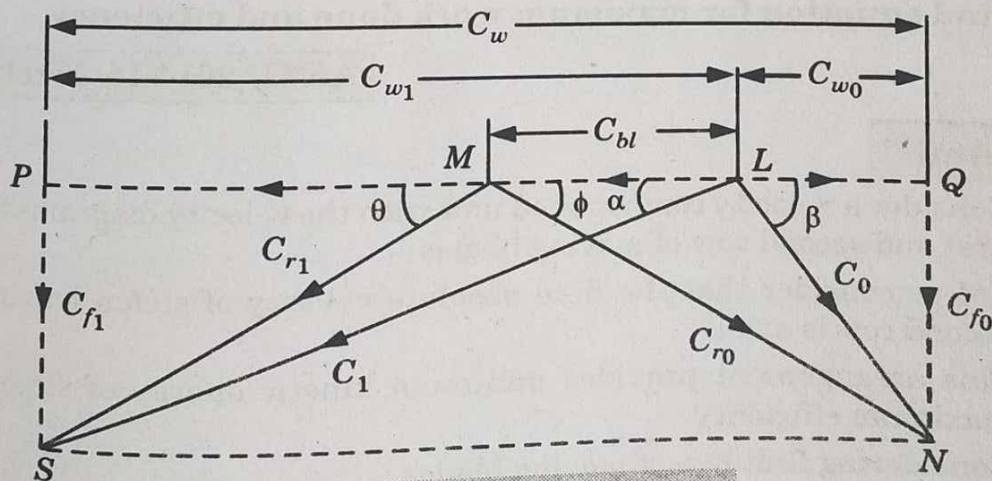


Fig. 4.18.1. Velocity diagram.

3. From Fig. 4.18.1,

$$\begin{aligned} C_{r1} \cos \theta &= MP = LP - LM \\ &= C_1 \cos \alpha - C_{bl} \end{aligned}$$

So,

$$C_w = (C_1 \cos \alpha - C_{bl})(1 + KZ)$$

4. Put this value into eq. (4.18.1),

$$\eta_{bl} = \frac{2C_{bl}(C_1 \cos \alpha - C_{bl})(1 + KZ)}{C_1^2} \quad \dots(4.18.2)$$

5. Let ratio of blade velocity to steam velocity is ρ . It is called blade velocity ratio. It is given as,

$$\rho = \frac{C_{bl}}{C_1}$$

6. From eq. (4.18.2), $\eta_{bl} = 2\rho (\cos \alpha - \rho) (1 + KZ)$... (4.18.3)

7. Differentiate eq. (4.18.3) wrt ρ , $\frac{d\eta_{bl}}{d\rho} = 2 (\cos \alpha - 2\rho) (1 + KZ)$

8. For maximum value, $\frac{d\eta_{bl}}{d\rho} = 0$

$$2 (\cos \alpha - 2\rho) (1 + KZ) = 0$$

$$\rho = \frac{\cos \alpha}{2}$$

9. Put this value in eq. (4.18.3),

$$\begin{aligned} (\eta_{bl})_{\max} &= 2 \times \frac{\cos \alpha}{2} \left(\cos \alpha - \left(\frac{\cos \alpha}{2} \right) \right) (1 + KZ) \\ &= (1 + KZ) \frac{\cos^2 \alpha}{2} \end{aligned}$$

10. For perfectly smooth and symmetrical blade, $K = Z = 1$
Hence, maximum efficiency of blade, $(\eta_{bl})_{\max} = \cos^2 \alpha$

Que 4.19. Draw velocity diagram for velocity compounded turbine and find equation for maximum work done and efficiency.

AKTU 2014-15, Marks 10

Answer

1. Consider a velocity compounded unit with the velocity diagrams for the first and second row of moving blades.
2. Let us consider that the final absolute velocity of steam leaving the second row is axial.
3. This arrangement provides minimum kinetic energy of steam and maximum efficiency.

4. Considering first row of moving blades :

- i. Work done per kg of steam, $W_1 = C_{bl} (C_{w1} + C_{w2})$

Here, $C_{w1} + C_{w2} = C_{r1} \cos \theta + C_{r0} \cos \phi$

- ii. In case of no friction loss and symmetrical blading

$$C_{r1} = C_{r0} \text{ and } \theta = \phi$$

So, $W_1 = C_{bl} \times 2C_{r1} \cos \theta$

- iii. From ΔLSP and ΔMSP

$$C_{r1} \cos \theta = C_1 \cos \alpha - C_{bl}$$

So, $W_1 = 2C_{bl} (C_1 \cos \alpha - C_{bl})$

- iv. The absolute velocity of steam leaving the first row should be equal to the absolute velocity of steam entering into the second row of moving blades.

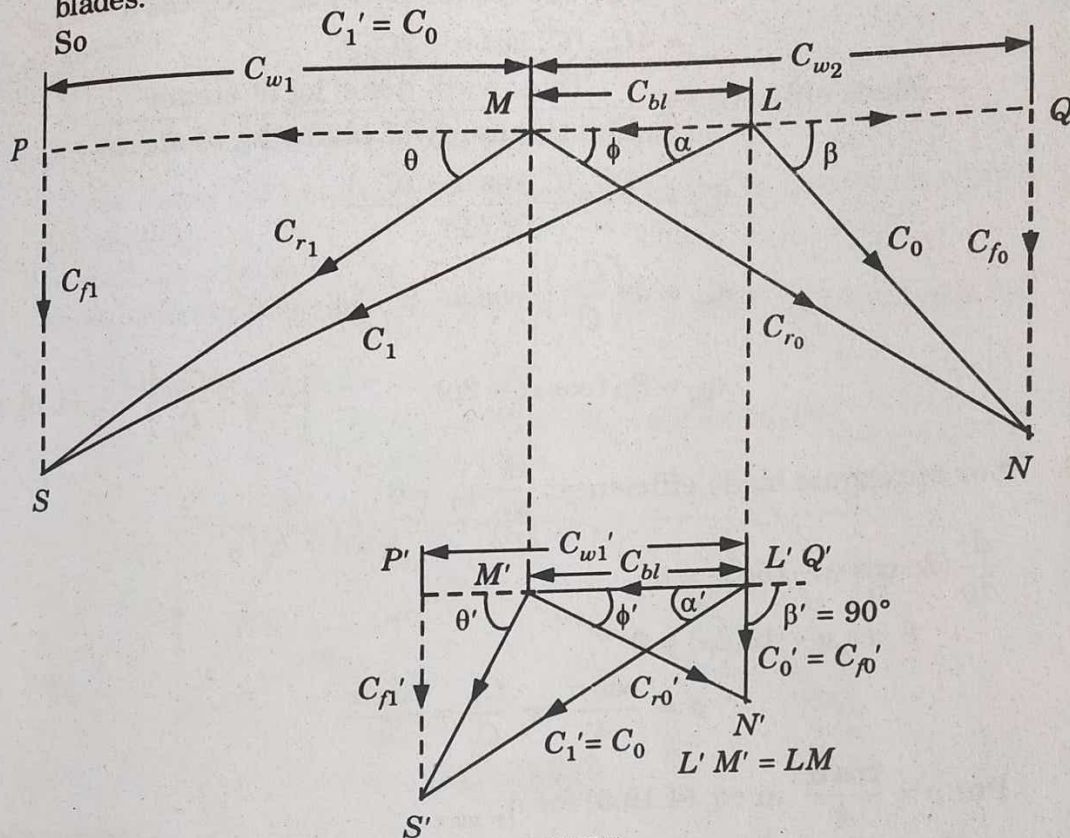


Fig. 4.19.1.

5. Considering second row of moving blades :

- Work done per kg of steam, $W_2 = C_{bl} C'_{w1}$
- As for axial discharge, $\beta' = 90^\circ$ and $C'_{w2} = 0$
- From $\Delta M'N'L'$ and $\Delta M'S'P'$, $C'_{w1} = C'_{r1} \cos \theta' + C'_{r0} \cos \phi'$
- As we assume that blades are symmetrical and there is no friction loss.

So,

$$C'_{r1} = C'_{r0} \text{ and } \theta' = \phi'$$

$$W_2 = C_{bl} (C'_{r1} \cos \theta' + C'_{r0} \cos \phi')$$

$$= 2C_{bl} C'_{r1} \cos \theta' = 2C_{bl} (C'_1 \cos \alpha' - C'_{bl}) \dots (4.19.1)$$

Now,

$$\alpha' = \beta$$

So,

$$C'_1 \cos \alpha' = C_0 \cos \beta$$

$$= C_{r0} \cos \phi - C_{bl} = C_{r1} \cos \theta - C_{bl} \left\{ \because C_{r0} = C_{r1} \right. \\ \left. \text{and } \theta = \phi \right\}$$

$$= C_1 \cos \alpha - C_{bl} - C_{bl} = C_1 \cos \alpha - 2C_{bl}$$

Put the value of $C'_1 \cos \alpha'$ in eq. (4.19.1),

$$W_2 = 2C_{bl} (C_1 \cos \alpha - 2C_{bl} - C_{bl})$$

$$W_2 = 2C_{bl} (C_1 \cos \alpha - 3C_{bl})$$

6. Total work done per kg of steam passing through both stages is,

$$\begin{aligned} W &= W_1 + W_2 \\ &= 2C_{bl}(C_1 \cos \alpha - C_{bl}) + 2C_{bl}(C_1 \cos \alpha - 3C_{bl}) \\ &= 4C_{bl}(C_1 \cos \alpha - 2C_{bl}) \quad \dots(4.19.2) \end{aligned}$$

7. Blade efficiency = $\frac{\text{Total work done/kg of steam}}{\text{Kinetic energy of blade/kg of steam}}$

$$\begin{aligned} \eta_{bl} &= \frac{4C_{bl}(C_1 \cos \alpha - 2C_{bl})}{(C_1^2/2)} \\ \eta_{bl} &= 8\left(\frac{C_{bl}}{C_1}\right)\left(\cos \alpha - 2\frac{C_{bl}}{C_1}\right) \\ \eta_{bl} &= 8\rho(\cos \alpha - 2\rho) \quad \left\{ \because \rho = \frac{C_{bl}}{C_1} \right\} \quad \dots(4.19.3) \end{aligned}$$

8. For maximum blade efficiency, $\frac{d}{d\rho} \eta_{bl} = 0$

$$\begin{aligned} \frac{d}{d\rho} (8\rho \cos \alpha - 16\rho^2) &= 0 \\ 8 \cos \alpha - 16(2\rho) &= 0 \\ \rho &= \frac{\cos \alpha}{4} \text{ or } \frac{C_{bl}}{C_1} = \frac{\cos \alpha}{4} \end{aligned}$$

Put $\rho = \frac{\cos \alpha}{4}$ in eq. (4.19.3) for $\eta_{bl \max}$

$$\begin{aligned} \eta_{bl \max} &= 8 \frac{\cos \alpha}{4} \left(\cos \alpha - 2 \frac{\cos \alpha}{4} \right) \\ \eta_{bl \max} &= \cos^2 \alpha \end{aligned}$$

9. For maximum work done, put $C_1 \cos \alpha = 4C_{bl}$ in eq. (4.19.2),

$$W_{\max} = 4C_{bl}(4C_{bl} - 2C_{bl}) = 8C_{bl}^2$$

Que 4.20. In a single stage simple impulse turbine the steam flows at rate of 5 kg/s. It has rotor of 1.2 m diameter running at 3000 rpm. Nozzle angle is 18° , blade speed ratio is 0.4, velocity coefficient is 0.9, outlet angle of blade is 3° less than inlet angle. Determine blade angles and power developed.

AKTU 2016-17, Marks 10

Answer

Given : $C_{bl}/C_1 = 0.4$, $C_{r0}/C_{r1} = 0.9$, $\alpha = 18^\circ$, $\phi = \theta - 3^\circ$, $N = 3000 \text{ rpm}$,

$D = 1.2 \text{ m}$, $\dot{m} = 5 \text{ kg/s}$

To Find :

- Blade angles.
- Power developed.

1. We know that, $C_{bl} = \frac{2 \times \pi \times 3000 \times 1.2}{60 \times 2} = 188.5 \text{ m/s}$
2. Since $\rho = \frac{C_{bl}}{C_1}$
 $\therefore C_1 = \frac{188.5}{0.4} = 471.25 \text{ m/s}$
3. Using these parameters the velocity diagram is drawn as shown in Fig. 4.20.1.
 Scale 1 cm = 50 m/s
4. From velocity diagram, $\phi = 29^\circ$, $\theta = 26^\circ$, $\Delta C_w = 495 \text{ m/s} = \text{Length } PQ$
5. Power developed = $\dot{m} C_{bl} \Delta C_w$
 $= 5 \times 188.5 \times 495 = 466537.5 \text{ J/s}$
 $= 466.54 \text{ kW}$

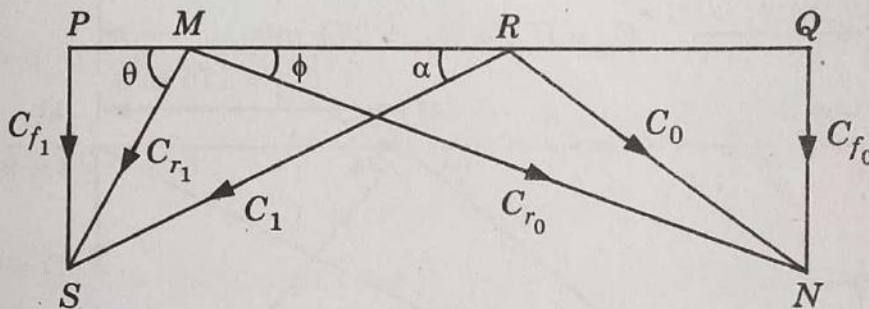


Fig. 4.20.1.

Que 4.21. An impulse steam turbine of 180 kW has steam flowing at rate of 165 kg/min and leaving axially. Steam turbine blade speed is 175 m/s and it leaves nozzle at 400 m/s. For the blade velocity coefficient of 0.9. Find nozzle angle, blade angles at inlet and exit, axial thrust and diagram efficiency.

AKTU 2015-16, Marks 10

Answer

Given : $P = 180 \text{ kW}$, $C_{bl} = 175 \text{ m/s}$, $C_1 = 400 \text{ m/s}$

$\dot{m}_s = 165 \text{ kg/min} = \frac{165}{60} = 2.75 \text{ kg/s}$, $K = 0.9$

To Find :

- i. Nozzle angle.
- ii. Blade angles at inlet and exit.
- iii. Axial thrust.
- iv. Diagram efficiency.

1. Power developed, $P = \frac{\dot{m}_s (C_{w_1} + C_{w_0}) \times C_{bl}}{1000} \text{ kW}$

$$180 = \frac{2.75 (C_{w1} + C_{w0}) \times 175}{1000}$$

$$(C_{w1} + C_{w0}) = \frac{180 \times 1000}{2.75 \times 175}$$

$$C_{w0} = 0 \text{ (Since the discharge is axial)}$$

$$C_{w1} = 374 \text{ m/s}$$

$$\frac{C_{r0}}{C_{r1}} = K = 0.9, \beta = 90^\circ$$

2. From ΔPQS , $\cos \alpha = \frac{C_w}{C_1} = \frac{C_{w1} + C_{w0}}{C_1}$

$$C_{w1} = C_1 \cos \alpha$$

$$C_{w1} = 400 \cos \alpha$$

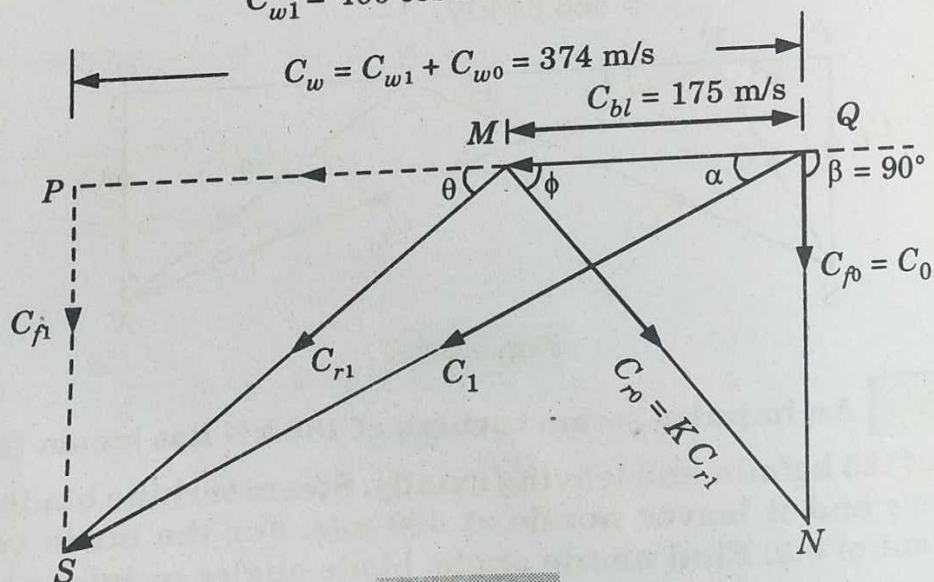


Fig. 4.21.1.

3. Nozzle angle, $\alpha = \cos^{-1} \left(\frac{374}{400} \right) = 20.77^\circ$

$$C_{f1} = C_1 \sin \alpha = 400 \sin (20.77^\circ) = 141.84 \text{ m/s}$$

4. In ΔPMS , $\tan \theta = \frac{C_{f1}}{C_w - C_{bl}}$

$$\text{Blade inlet angle, } \tan \theta = \frac{141.84}{374 - 175} = 0.712$$

$$\theta = \tan^{-1} (0.712)$$

$$\theta = 35.45^\circ$$

$$C_{r1} \sin \theta = C_{f1} \Rightarrow C_{r1} = \frac{141.84}{\sin (35.45^\circ)}$$

$$C_{r1} = \frac{141.84}{0.5799} = 244.59 \text{ m/s}$$

$$C_{r0} = K C_{r1}$$

$$C_{r0} = 0.9 \times 244.59 \text{ m/s} = 220.13 \text{ m/s}$$

5. In ΔQMN ,

$$\text{Blade outlet angle, } \cos \phi = \frac{C_{bl}}{C_{r0}} = \frac{175}{220.13} = 0.794$$

$$\phi = \cos^{-1}(0.794) = 37.43^\circ$$

$$\tan \phi = \frac{C_{f0}}{C_{bl}} = \frac{C_{f0}}{175}$$

$$C_{f0} = 175 \times \tan(37.43^\circ) = 133.94 \text{ m/s}$$

$$\begin{aligned} 6. \quad \text{Axial thrust} &= \dot{m}_s \times (C_{f1} - C_{f0}) \\ &= 2.75 \times (141.84 - 133.94) \\ &= 21.725 \text{ N} \end{aligned}$$

7. Blade or diagram efficiency,

$$\begin{aligned} \eta_{bl} &= \frac{2 C_{bl} \times (C_{w1} + C_{w0})}{C_1^2} = \frac{2 \times 175 \times 374}{(400)^2} \\ &= 0.8181 \text{ or } 81.81\% \end{aligned}$$

Que 4.22. The following data refer to a single stage impulse turbine : Isentropic nozzle heat drop = 251 kJ/kg ; nozzle efficiency = 90 % ; nozzle angle = 20° ; ratio of blade speed to whirl component of steam speed = 0.5 ; blade velocity coefficient = 0.9 ; the velocity of steam entering the nozzle = 20 m/s. Determine :

- The blade angles at inlet and outlet if the steam enters into the blades without shock and leaves the blades in an axial direction.
- Blade efficiency.
- Power developed and axial thrust in an axial direction.

AKTU 2015-16, Marks 15

Answer

Given : Isentropic heat drop = 251 kJ/kg

$$\eta_{\text{nozzle}} = \eta_{bl} = 90\%, \alpha = 20^\circ, C_{bl}/C_w = 0.5, K = , C_{r0}/C_{r1} = 0.9$$

Velocity of steam entering the nozzle = 20 m/s

- Nozzle efficiency is given by :

$$\eta_{\text{nozzle}} = \frac{\text{Useful heat drop}}{\text{Isentropic heat drop}}$$

or

$$0.9 = \frac{\text{Useful heat drop}}{251}$$

- ∴ Useful heat drop = $0.9 \times 251 = 225.9 \text{ kJ/kg}$
 2. Applying the energy equation to the nozzle, we get

$$\frac{C_1^2 - 20^2}{2} = 225.9 \times 1000$$

$$\therefore C_1^2 = 2 \times 225.9 \times 1000 + 400 = 452200$$

$$C_1 = 672.4 \text{ m/s}$$

$$C_0 = C_{r0}$$

3. With the above data construct the velocity triangles as follows:
 i. Select a suitable scale, say $1 \text{ cm} = 50 \text{ m/s}$.
 ii. Draw a horizontal line through a point L and angle $\alpha = 20^\circ$. Mark the point along LS as

$$LS = C_1 = 672.4 \text{ m/s} = \frac{672.4}{50} = 13.448 \text{ cm}$$

- iii. Draw a line through S which is perpendicular to the horizontal line through L and it cuts at the point P . Measure the distance

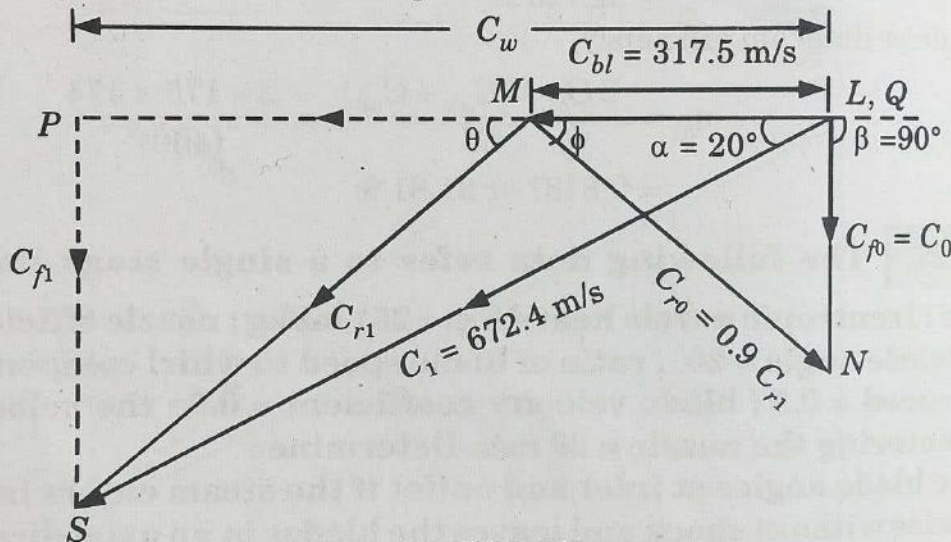


Fig. 4.22.1.

$$LP = 12.7 \text{ cm}$$

$$\therefore C_{w1} = C_w = 12.7 \text{ cm}$$

and

$$C_{bl} = 0.5 C_w = 0.5 \times 12.7 = 6.35 \text{ cm}$$

- iv. Mark the point M as $LM = C_{bl} = 6.35 \text{ cm}$.
 v. Join point MS and complete the inlet velocity triangle LMS .
 vi. Measure MS (C_{r1}) = 7.7 cm .
 Now, $C_{r0} = K \times C_{r1} = 0.9 \times 7.7 = 6.93 \text{ cm}$
 vii. Draw a perpendicular line through point L to the line LM . From M cut an arc of radius 6.93 cm to cut the vertical line through L and mark the point N and join MN which completes the outlet triangle LMN .
 4. Now find out velocities converting lengths into velocities,

$$C_1 = 672.4 \text{ m/s}$$

$$C_w = 12.7 \text{ cm} = 12.7 \times 50 = 635 \text{ m/s}$$

$$C_{bl} = 0.5 C_w = 0.5 \times 635 = 317.5 \text{ m/s}$$

$$C_{r1} = 7.7 \text{ cm} = 7.7 \times 50 = 385 \text{ m/s}$$

$$C_{r0} = 0.9 C_{r1} = 0.9 \times 385 = 346.5 \text{ m/s}$$

$$C_{f1} = 4.45 \text{ cm} = 4.45 \times 50 = 222.5 \text{ m/s}$$

$$C_{f0} = 2.6 \text{ cm} = 2.6 \times 50 = 130 \text{ m/s}$$

5. By measurement, from velocity triangle blade angles at inlet and outlet are obtained as follows :

$$\theta = 35^\circ, \phi = 22^\circ$$

6. Blade efficiency, $\eta_{bl} = \frac{2C_{bl}C_w}{C_1^2} = \frac{2 \times 317.5 \times 635}{(672.4)^2}$
 $= 0.89 \text{ or } 89 \%$

7. Power developed, $P = \frac{(C_{w1} + C_{w0}) C_{bl}}{1000} = \frac{(635 + 0) \times 317.5}{1000}$
 $= 201.61 \text{ kW}$

8. Axial thrust $= (C_{f1} - C_{f0}) = (222.5 - 130) = 92.5 \text{ N}$

Que 4.23. In a single stage impulse turbine the enthalpy drop of 200 kJ/kg occurs in the nozzle having efficiency of 96 % and nozzle angle of 15° . The blade velocity coefficient is 0.96 and ratio of blade speed to steam velocity is 0.5. The steam mass flow rate is 20 kg/s and velocity of steam entering is 50 m/s. Determine :

- The blade angles at inlet and outlet if the steam enters blades smoothly and leaves axially.
- The blade efficiency.
- The power developed in kW.
- The axial thrust.

Solve using velocity diagram.

AKTU 2016-17, Marks 15

Answer

Given : Enthalpy drop $= 200 \text{ kJ/kg}$, $C_{bl}/C_1 = 0.5$,

$C_{r0}/C_{r1} = 0.96$, $\dot{m}_s = 20 \text{ kg/s}$, $\alpha = 15^\circ$, $C = 50 \text{ m/s}$

1. Actual enthalpy drop in nozzle, $\Delta h_N = 200 \times 0.96 = 192 \text{ kJ/kg}$

2. Velocity of steam leaving nozzle, $C_1 = \sqrt{2 \Delta h_N + (C)^2}$
 $= \sqrt{2 \times 192 \times 10^3 + (50)^2}$
 $= 621.69 \text{ m/s}$

$$C_{bl} = 0.5 \times 621.69 = 310.845 \text{ m/s} \quad \left(\because \frac{C_{bl}}{C_1} = 0.5 \right)$$

3. Let us draw the velocity diagram across blade as shown in Fig. 4.23.1.
 Let us use scale as $1 \text{ cm} = 100 \text{ m/s}$.

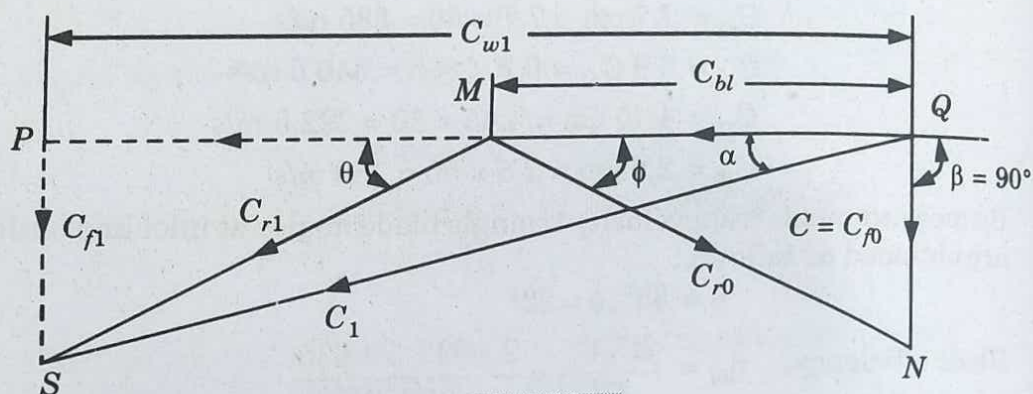


Fig. 4.23.1.

4. From velocity triangle,

$$QS = C_1 = 621.69 \text{ m/s}, QM = C_{bl} = 310.845 \text{ m/s}$$

Length MS gives C_{r1} , from measurement it is seen to be 3.3 cm.

Hence, $C_{r1} = 300 \text{ m/s}$, so $C_{r0} = 0.96 \times 330$
 $C_{r0} = 316.8 \text{ m/s}$

5. Also from velocity diagram,

$$\theta = 28.5^\circ, \phi = 12^\circ, C_{w1} = 595 \text{ m/s}, C_{w0} = 0$$

$$C_{f1} = 170 \text{ m/s}, C_{f0} = 75 \text{ m/s}$$

Blade angle at inlet = 28.5°

Blade angle at exit = 12°

6. Blade efficiency = $\frac{2 C_{bl} (C_{w1} + C_{w0})}{C_1^2} = \frac{2 \times 310.845 \times 595}{(621.69)^2}$
 $= 0.9571 = 95.71 \%$

7. Power developed = $\dot{m}_s (C_{w1} + C_{w0}) C_{bl} = 20 \times 595 \times 310.845$
 $= 3699055.5 \text{ J/s}$
 $= 3699.05 \text{ kJ/s}$

8. Axial thrust, $F_a = \dot{m}_s (C_{f1} - C_{f0})$
 $= 20 \times (170 - 75)$
 $= 1900 \text{ N}$

Que 4.24. In an impulse turbine the steam issues from the nozzle with a velocity of 1200 m/s. Nozzle angle is 20° and mean blade velocity is 400 m/s. The blades are equiangular. The mass flow rate is 1000 kg/min and friction factor is 0.8. Determine : (i) Blade angles, (ii) Axial thrust, (iii) Power, (iv) Blade efficiency. (v) Stage efficiency if nozzle efficiency is 93 %.

AKTU 2017-18, Marks 07

Answer

Given : $C_1 = 1200 \text{ m/s}$, $\alpha = 20^\circ$, $C_{bl} = 400 \text{ m/sec}$, $K = 0.8$,
 $\eta_{\text{nozzle}} = 0.93$, $\dot{m} = 1000 \text{ kg/min} = 16.6 \text{ kg/s}$

- $$C_{r1} = 840 \text{ m/s}$$

$$C_{r0} = KC_{r1} = 0.8 \times 840 = 672 \text{ m/s}$$

2. Also

$$\text{Axial thrust} = m(C_{f1} - C_{f2}) = 16.6 (430 - 360)$$

$$= 1166.67 \text{ N}$$

- #### 4. Power,

$$P = \frac{mC_w C_{bl}}{1000} = \frac{1000 \times 1280 \times 400}{1000 \times 60}$$

$$= 8533.34 \text{ kW}$$

6. Blade efficiency, $\eta_{bl} = \frac{2C_w C_{bl}}{C_1^2} = \frac{2 \times 1280 \times 400}{(1200)^2}$

$$= 0.711 = 71.1 \%$$

7. Stage efficiency, $\eta_{\text{stage}} = \eta_{bl} \times \eta_{\text{nozzle}} = 0.711 \times 0.93$

$$= 0.661 = 66.1 \%$$

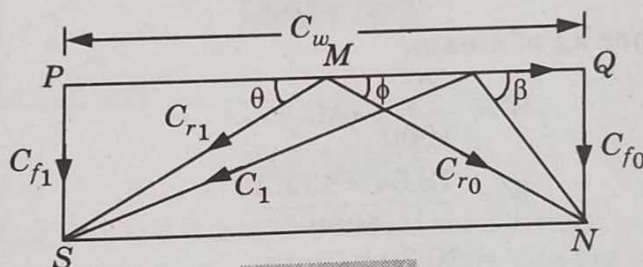


Fig. 4.24.1.

Que 4.25. In a Parson turbine running at 1500 rpm, the available enthalpy drop for an expansion is 65 kJ/kg. If the mean diameter of the rotor is 100 cm, find the number of rows of moving blades. Assume stage efficiency = 80 %, speed ratio 0.7, and blade outlet angle = 20° .

AKTU 2018-19, Marks 07

AKTU 2018-19, Marks 07

Answer

Given : $N = 1500 \text{ rpm}$, $D = 100 \text{ cm} = 1 \text{ m}$, $\eta_s = 0.8$, $\alpha = 20^\circ$,
 $\phi' = 0.7$, $\Delta h = 65 \text{ kJ/kg}$

To Find : Number of rows of moving blades.

1. Tangential speed of rotor,

$$C_{bl} = \frac{\pi DN}{60} = \frac{\pi \times 1 \times 1500}{60} = 78.54 \text{ m/s}$$

2. Steam velocity at inlet,

$$C_1 = \frac{C_{bl}}{\phi'} = \frac{78.54}{0.7} = 112.2 \text{ m/s}$$

3. From velocity triangle,

$$\begin{aligned} \Delta C_u &= C_1 \cos \alpha + (C_{r2} \cos \beta - C_{bl}) \\ &= C_1 \cos \alpha + C_1 \cos \alpha - C_{bl} \quad (\because \alpha = \phi \text{ as } C_{r2} = C_1) \\ &= 2C_1 \cos \alpha - C_{bl} \\ &= 2 \times 112.2 \times \cos 20^\circ - 78.54 \\ &= 132.33 \text{ m/s} \end{aligned}$$

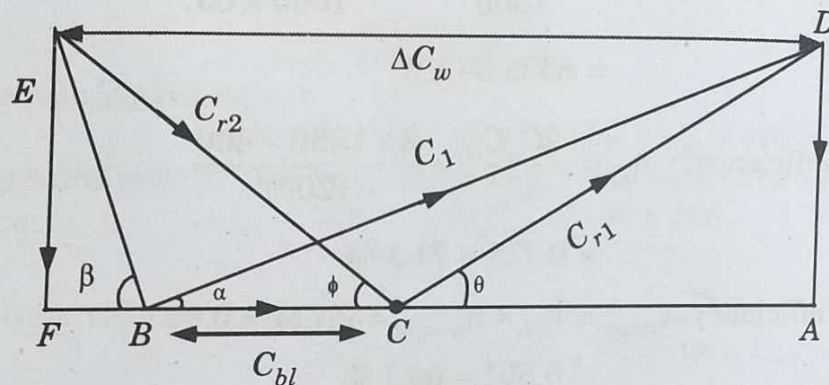


Fig. 4.25.1.

4. Work done per kg of steam,

$$W = \frac{C_{bl}}{1000} (\Delta C_u)$$

$$\begin{aligned} W &= \frac{78.54 \times 132.33}{1000} \\ &= 10.39 \text{ kJ/kg} \end{aligned}$$

5. Stage efficiency, $\eta_s = \frac{W}{\Delta h} \times \text{Number of rows of moving blades}$

$$0.8 = \frac{10.39 \times N}{65}$$

$$N = \frac{0.8 \times 65}{10.39} = 5$$

PART-9

State Point Locus, Losses in Steam Turbines.

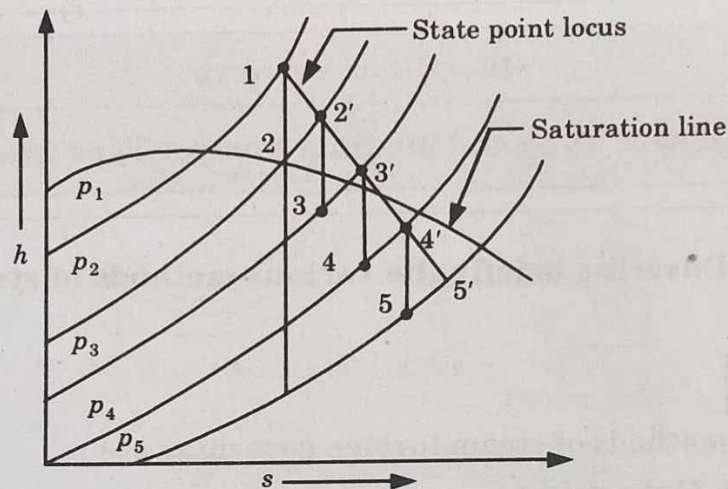
Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 4.26. Explain state point locus.

Answer

1. State point is a point on h - s diagram (or Mollier diagram) that represents the condition of steam at that instant.
2. In real condition, the steam leaving turbine have higher enthalpy than the enthalpy of steam at exit under isentropic expansion.
3. From the diagram shown in Fig. 4.26.1, this situation becomes clear as process 1-2 is the isentropic process and 1-2' is actual process so 2' has more enthalpy than enthalpy at point 2.

**Fig. 4.26.1.**

5. The points 2', 3', 4', and 5' are the actual condition of steam at exit.
6. The line joining these points is called condition line or state point locus.

Que 4.27. What are the various losses in steam turbines ?

Answer

Following are the various losses in steam turbines :

1. **Loss in Nozzles :** The expansion is not isentropic in nature. In nozzle it deviates which causes loss in kinetic energy of steam.
2. **Loss in Moving Blades :** Blade friction causes loss in relative velocity of steam. Loss of energy occurs during passage of steam from one stage to other. This loss is also known as carry over loss.
3. **Windage Loss :** When moving rotor blades came in contact with inactive steam then there is transfer of energy from blade to steam. This loss of energy from rotor to fluid is termed as windage loss.
4. **Loss due to Leakage :** Steam leakage may occur across the turbine shaft and between stages. This leads to partial utilization of production work.
5. **Loss in Bearing :** The bearings support the high speed rotating shaft and about 1% loss of turbine output occurs in bearing.

6. **Losses at Inlet and Exit :** Near the entry and exit valve, steam pressure becomes low.
7. **Radiation Loss :** These losses are very small or negligible in steam turbines but in gas turbine these losses are high as compared to steam turbine.

PART-10

Governing of Steam Turbines, Comparison With Steam Engine.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 4.28. Describe briefly the various methods of steam turbine governing.

Answer

Various methods of steam turbine governing are :

A. Throttle Governing :

1. Throttle governing is most widely used particularly on small turbines, because its initial cost is less and the mechanism is simple.
2. The objective of throttle governing is to throttle the steam, whenever, there is a reduction of load compared to economic or design load for maintaining speed and vice versa.

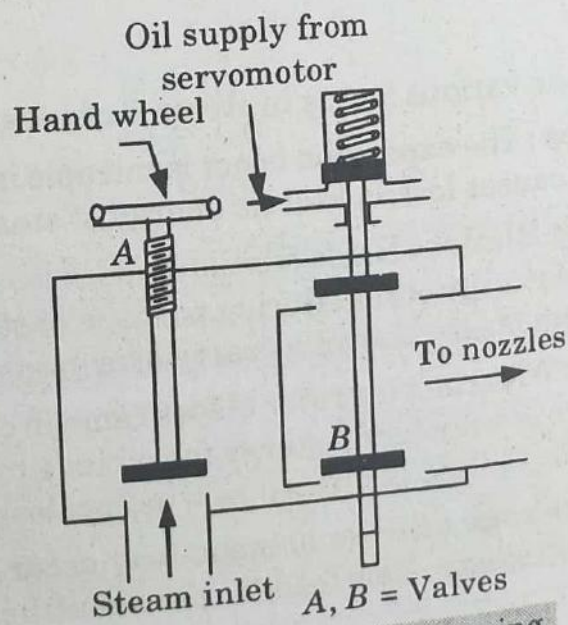
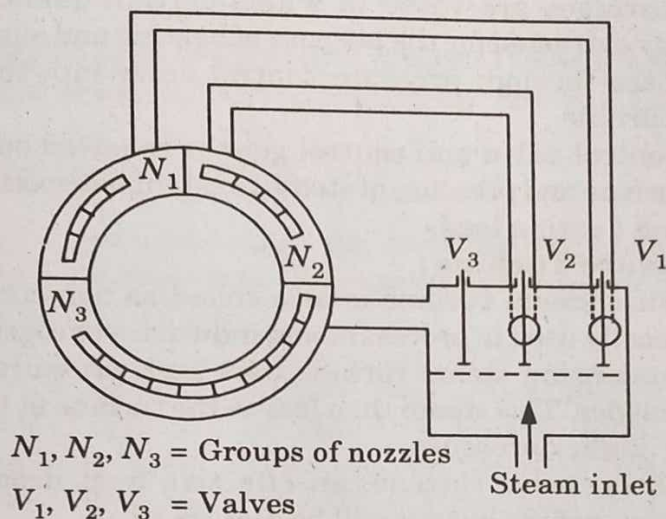


Fig. 4.28.1. Throttle governing.

B. Nozzle Governing :

1. The efficiency of a steam turbine is considerably reduced if throttle governing is carried out at low loads. An alternative and more efficient form of governing is by means of nozzle control.
2. In this method of governing, the nozzles are grouped together 3 to 5 or more groups and supply of steam to each group is controlled by regulating valves.

**Fig. 4.28.2. Nozzle governing.**

3. Under full load conditions the valves remain fully open.
4. When the load on the turbine becomes more or less than the design value, the supply of steam to a group of nozzles may be varied accordingly so as to restore the original speed.

Que 4.29. Compare steam turbine with steam engine.

Answer

S.No.	Steam Turbine	Steam Engine
1.	It has high thermal efficiency.	It has low thermal efficiency.
2.	No flywheel is required.	Flywheel is required.
3.	Much higher speeds and greater range of speed is possible.	Much higher speed and greater range of speed is not possible.
4.	Balancing problem is minimised due to absence of reciprocating parts.	Balancing problem arises due to presence of reciprocating parts.
5.	No internal lubrication is required.	Internal lubrication is required.

Que 4.30. Describe pass out turbines and back pressure turbines.

AKTU 2018-19, Marks 07

Answer

A. Pass Out Turbine :

1. Pass out turbines are those in which certain quantity of steam is continuously extracted for the purpose of heating and allowing remaining steam to pass through pressure control valve into the low pressure section of turbine.
2. Pressure control valve and control gear is required so as to keep the speeds of turbine and pressure of steam constant irrespective of variations of power and heating loads.

B. Back Pressure Turbine :

1. Back pressure steam turbine is also called as non-condensing steam turbine is mostly used in process steam industries or cogeneration plants.
2. The non-condensing steam turbine uses high pressure steam for the rotation of blades. This steam then leaves the turbine at the atmospheric pressure or higher pressure.
3. In the back pressure turbine, an effective heat drop will be small therefore, the turbine output will be also small.
4. As the back pressure turbine consists of fewer turbine stages with simple structure and small exhaust parts, this results in lower equipment costs.
5. It requires very less or no cooling water. Its efficiency is higher as it does not reject heat in the condensation process.

VERY IMPORTANT QUESTIONS

Following questions are very important. These questions may be asked in your SESSIONALS as well as UNIVERSITY EXAMINATION.

Q. 1. Define the steam nozzle. Also derive the expressions for velocity of steam and discharge through steam nozzle.

Ans. Refer Q. 4.3, Unit-4.

Q. 2. What do you mean by choked flow ? Explain and write effect of friction on nozzle.

Ans. Refer Q. 4.7, Unit-4.

Q. 3. In a steam nozzle steam expands from 16 bar to 5 bar with initial temperature of 300°C and mass flow of 1 kg/s . Determine the throat and exit areas considering

5

UNIT

Gas Turbine and Jet Propulsion

CONTENTS

Part-1	: Gas Turbine Classification, Brayton Cycle	5-2A to 5-4A
Part-2	: Principles of Gas Turbine	5-4A to 5-6A
Part-3	: Gas Turbine Cycles with Intercooling, Reheat and Regeneration and their Combinations	5-6A to 5-16A
Part-4	: Stage Efficiency, Polytropic Efficiency, Deviation of Actual Cycles from Ideal Cycles	5-16A to 5-18A
Part-5	: Introduction to the Principles of Jet Propulsion	5-18A to 5-20A
Part-6	: Turbojet and Turboprop Engines and their Processes	5-20A to 5-25A
Part-7	: Principle of Rocket Propulsion, Introduction to Rocket Engine	5-25A to 5-26A
Part-8	: Reciprocating Compressors, Staging of Reciprocating Compressors	5-26A to 5-30A
Part-9	: Optimal Stage Pressure Ratio, Effect of Intercooling, Minimum Work for Multistage Reciprocating Compressors	5-30A to 5-32A

PART-1*Gas Turbine Classification, Brayton Cycle.***Questions-Answers****Long Answer Type and Medium Answer Type Questions**

Que 5.1. What do you mean by gas turbine ? How are gas turbines classified ?

Answer**A. Gas Turbine :**

1. A gas turbine is a rotary engine that extracts energy from a flow of combustion gas.
2. A rotary compressor driven by the turbine compresses the air used for combustion, power being taken either as torque from the turbine or thrust from the expanding gases.
3. A simple gas turbine plant consists of an air compressor and combustion chamber to supply hot gases to gas turbine.
4. After the plant is started with the help of an auxiliary engine, air is drawn into the compressor where pressure is raised.
5. The compressed air then drawn into combustion chamber.
6. The resulting product of combustion enters the turbine at a higher temperature where they expand and finally discharged to the atmosphere through exhaust pipe.

B. Classification : Gas turbine mainly classified into two categories :

1. Constant pressure combustion gas turbine :
 - i. Open cycle gas turbine.
 - ii. Closed cycle gas turbine.
2. Constant volume combustion gas turbine.

Que 5.2. Explain Brayton cycle and obtain expression for efficiency in terms of pressure and temperature ratio.

AKTU 2014-15, Marks 10**Answer****A. Brayton Cycle :**

1. It is a theoretical cycle for gas turbines and also known as constant pressure cycle for a perfect gas.

2. The basic components of a Brayton cycle are shown in Fig. 5.2.1.

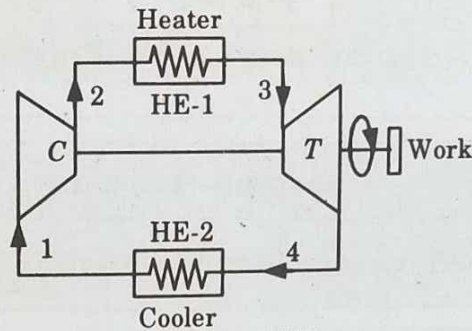


Fig. 5.2.1.

3. There occur two isentropic processes and two constant pressure processes. Compression and expansion of working fluid is done by isentropic process while addition and rejection of heat is done at constant pressure.
4. Brayton cycle on p - v and T - s diagram is shown in Fig. 5.2.2(a) and 5.2.2(b) respectively.

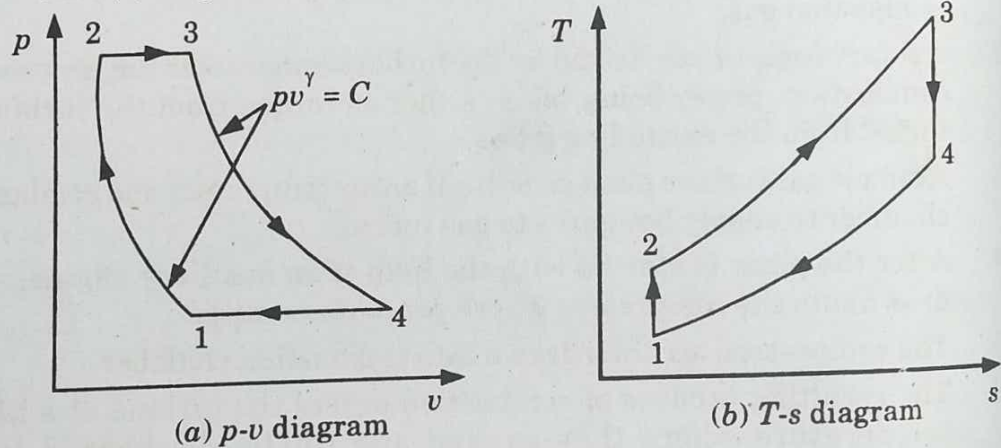


Fig. 5.2.2.

5. Brayton cycle shows following processes :
- 1-2 : Adiabatic compression.
 - 2-3 : Constant pressure heat addition.
 - 3-4 : Adiabatic expansion.
 - 4-1 : Constant pressure heat rejection.
6. Now, Work done / cycle = Heat added/cycle - Heat rejected/cycle
- Heat added in process 2-3 = $mC_p (T_3 - T_2)$
- Heat rejected in process 4-1 = $mC_p (T_4 - T_1)$
- Work done / cycle = $mC_p (T_3 - T_2) - mC_p (T_4 - T_1)$
- B. Efficiency of Brayton Cycle :**
1. Efficiency, $\eta_{\text{air-standard}} = \frac{\text{Work done / cycle}}{\text{Heat addition / cycle}}$

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

$$\eta_{\text{air-standard}} = 1 - \frac{T_4 - T_1}{T_3 - T_2} \quad \dots(5.2.1)$$

2. From process 1-2,

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1} \right)^{\frac{\gamma-1}{\gamma}} \quad \left(\because \frac{p_2}{p_1} = r_p = \text{Pressure ratio} \right)$$

$$T_2 = T_1 (r_p)^{\frac{\gamma-1}{\gamma}}$$

3. Similarly, from process 3-4,

$$T_3 = T_4 (r_p)^{\frac{\gamma-1}{\gamma}}$$

4. Putting the values of T_2 and T_3 in eq. (5.2.1), we get

$$\eta_{\text{air-standard}} = 1 - \frac{T_4 - T_1}{T_4 (r_p)^{\frac{\gamma-1}{\gamma}} - T_1 (r_p)^{\frac{\gamma-1}{\gamma}}} = 1 - \frac{1}{(r_p)^{\frac{\gamma-1}{\gamma}}}$$

PART-2

Principles of Gas Turbine.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 5.3. With neat sketches write short note on the working of a simple constant pressure open cycle gas turbine and closed gas turbine.

Answer

A. Working of Constant Pressure Open Cycle Gas Turbine :

1. In open cycle, a rotary compressor and a turbine are mounted on a common shaft.
2. Air is drawn into the compressor and then compressed air is drawn into the combustion chamber.
3. Here energy is supplied by the spraying fuel into the air stream.
4. After that hot gases expand through the turbine and exhaust to the atmosphere.

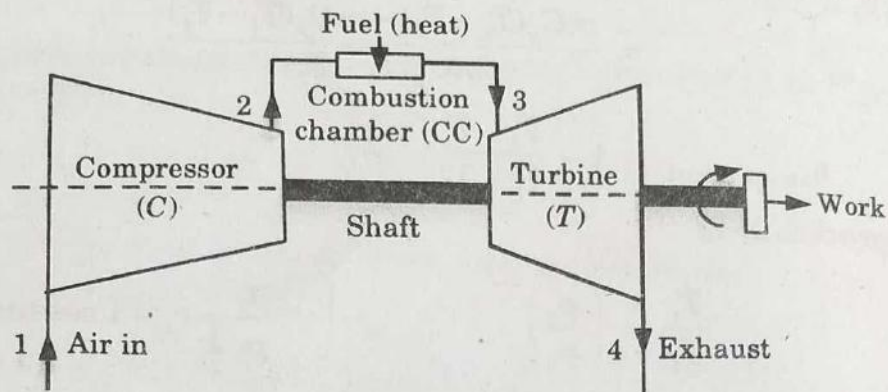


Fig. 5.3.1. Open cycle gas turbine.

B. Working of Constant Pressure Closed Cycle Gas Turbine :

1. As shown in Fig. 5.3.2 open cycle and closed cycle are same in all manners except in closed cycle after the exhaust air is send to a cooling medium so that it can be further used by the compressor.

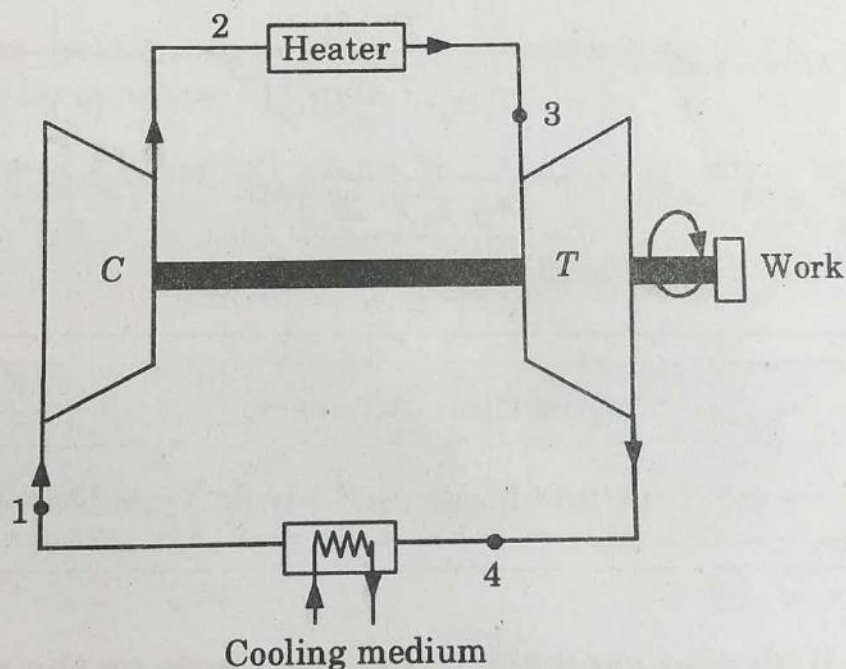


Fig. 5.3.2. Closed cycle gas turbine.

Que 5.4. Why are the back work ratios relatively high in gas turbine plants compared to those of steam power plants ?

AKTU 2015-16, Marks 7.5

Answer

1. Back work ratio may be defined as the ratio of negative work to the turbine work in power plant.
2. In gas turbine plants, air is compressed from turbine pressure to the combustion chamber pressure.

3. The work is given by $-\int v dp$. As specific volume of air is very high (even in close cycle gas turbine plants), the compressor work required is very high, and therefore a bulky compressor is needed.
4. In steam power plants, the turbine exhaust is changed to liquid phase in condenser.
5. The pressure of condensate is raised to boiler pressure by condensate extraction pump and boiler feed pump in series, since specific volume of water is very small as compared to that of air, the pump work $(-\int v dp)$, is also very small.
6. Hence for above reasons back work ratio for gas turbine plants is relatively high compared to those of steam power plants.

PART-3

Gas Turbine Cycles with Intercooling, Reheat and Regeneration and their Combinations.

Questions-Answers

Long Answer Type and Medium Answer Type Questions

Que 5.5. Explain in brief methods of improving efficiency of open cycle gas turbine.

AKTU 2014-15, Marks 10

OR

How regeneration in gas turbines increases thermal efficiency of the plant ?

AKTU 2014-15, Marks 10

Answer

Thermal efficiency or specific output of an open cycle gas turbine can be improved by following three methods :

- a. **Intercooling :**
 1. This is required to reduce the compressor work and to increase the work ratio.
 2. The compression of air is to be done in two compressors. Firstly in low pressure compressor then in high pressure compressor, compression process is to be done as shown in Fig. 5.5.1.

3. Fig. 5.5.1 shows ideal and actual processes which occur in an open cycle gas turbine. The dotted lines show the actual curve and thicker one shows the ideal curve.

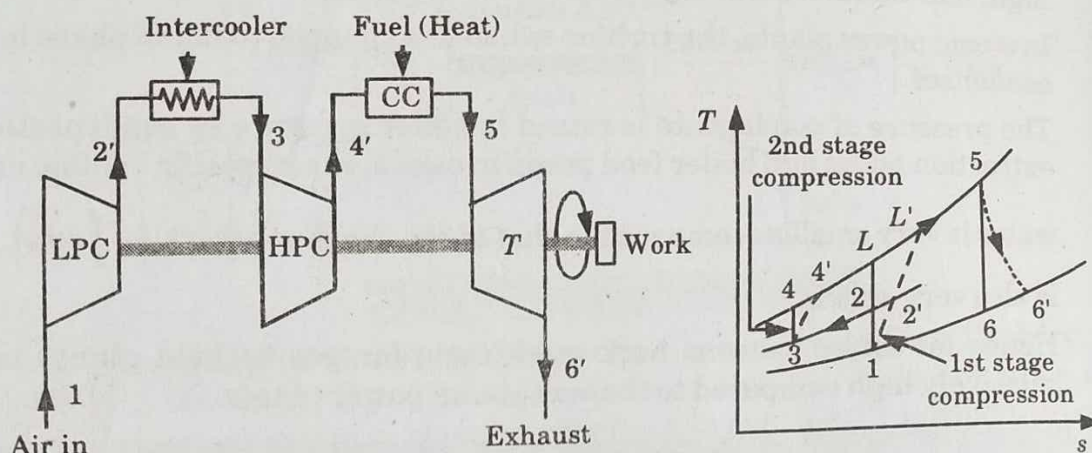


Fig. 5.5.1.

4. From T-s diagram,
 i. The process with intercooling is 1-2-3-4-5-6 (Ideal process) or 1-2'-3-4'-5-6' (Actual process).
 ii. The work required to run the compressor with intercooling is,
 For ideal condition, $W_{CI} = C_p (T_2 - T_1) + C_p (T_4 - T_3)$
 For actual condition, $W_{CI} = C_p (T_{2'} - T_1) + C_p (T_{4'} - T_3)$
 iii. The process 1-L-5-6 is ideal process without intercooling, whereas 1-L'-5-6' is actual process without intercooling.
 iv. The work required to run the compressor without intercooling is,

$$\begin{aligned} W_C &= C_p (T_L - T_1) \\ &= C_p (T_L - T_2 + T_2 - T_1) \\ &= C_p (T_L - T_2) + C_p (T_2 - T_1) \end{aligned}$$

For actual condition,

$$\begin{aligned} W_C &= C_p (T_{L'} - T_1) \\ &= C_p (T_{L'} - T_{2'} + T_{2'} - T_1) \\ &= C_p (T_{L'} - T_{2'}) + C_p (T_{2'} - T_1) \end{aligned}$$

5. On comparing both the work done it can be concluded that the work input with intercooling is less than the work input without intercooling. As it is clear from the T-s curve that

$$T_{L'} - T_{2'} > T_4 - T_3 \text{ (for actual process)}$$

and,

$$T_L - T_2 > T_4 - T_3 \text{ (for ideal process)}$$

But the heat supplied increases and this increase in heat supply leads to decrement in thermal efficiency.

UNIT 5

Gas Turbines and Jet Propulsion

CONCEPT OUTLINE 1

Gas turbine :

Classification : Gas turbines are classified as :

1. Constant pressure combustion gas turbine
2. Constant volume combustion gas turbine.

Brayton cycle : It is a constant pressure cycle for a perfect gas. It is also called Joule cycle. The heat transfers are achieved in reversible constant pressure heat exchangers. An ideal gas turbine plant would perform the processes that make up a Brayton cycle.

5.1. What do you mean by term 'gas turbine' ? How are gas turbines classified ? Also give the applications of gas turbine.

Ans. A gas turbine, also called a combustion turbine, is a rotary engine that extracts energy from a flow of combustion gas. A rotary compressor driven by the turbine compresses the air used for combustion, power being taken either as torque from the turbine or thrust from the expanding gases. It is used for the power generation. A simple gas turbine plant consists of an air compressor and combustion chamber to supply hot gases to gas turbine.

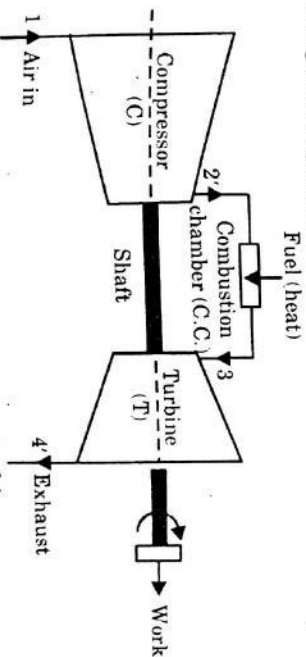


Fig. 5.1. Open cycle gas turbine.

After the plant is started with the help of an auxiliary engine, air is drawn into the compressor where pressure is raised. The compressed air then drawn into combustion chamber. The resulting product of combustion enters the turbine at a higher temperature where they expand and finally discharged to the atmosphere through exhaust pipe.

Classification : Gas turbine mainly divided into two groups :

1. Constant pressure combustion gas turbine
 - (a) Open cycle gas turbine
 - (b) Closed cycle gas turbine
2. Constant volume combustion gas turbine

Applications : Main applications of a gas turbine are :

1. in air craft.
2. in locomotive.
3. in marine engine.
4. in automobile engine.
5. in power generation.

5.2. Give merits and demerits of gas turbine.

Ans. Merits :

1. Mechanical efficiency of a gas turbine is quite higher than I.C. engine.
2. Gas turbine does not require flywheel. So torque on the shaft is continuous.
3. Cheaper fuel is used in gas turbine.
4. Gas turbine can be driven at a very high speed.
5. Exhaust from gas turbine is less polluting.

Demerits :

1. Thermal efficiency of a gas turbine is low as compared to an I.C. engine.
2. Due to higher operating speed of the turbine, it is facilitated with speed reduction device.
3. It is difficult to start a gas turbine as compared to an I.C. engine.
4. With wide operating speed the fuel control is comparatively difficult.
5. Manufacturing of blade is difficult due to use of nickel-chromium alloy.

5.3. Compare a gas turbine with internal combustion engine and steam turbine. [UPTU 2004-05, Marks 10]

Ans. Comparison of gas turbine with internal combustion engine :

Merits of gas turbine over I.C. Engine :

1. A gas turbine has simple mechanism as compared to I.C. engine.
2. Gas turbine works on higher speed as compared to I.C. engine.

3. Gas turbine has a weight reduction of 70 % as compared to I.C. engine.
4. Gas turbine requires small foundation and has easy balancing as compared to I.C. engine.
5. Gas turbine has low maintenance cost as compared to I.C. engine.
6. The phenomenon of detonation does not occur in a gas turbine.

Demerits of gas turbine over I.C. engine :

1. The main demerits of gas turbine are low full load thermal efficiency and poor part load efficiency.
2. Gas turbine is costly because of need of high heat resistant materials and manufacturing of turbine blades.
3. Gas turbine needs an auxiliary motor for starting.
4. The response towards acceleration is slow in gas turbine.
5. Due to high speed of gas turbine it requires reduction gears.

Comparison between gas turbine and steam engine :

1. Gas turbines are compact in size whereas steam turbines require bulky and expensive steam generators like boiler and nuclear reactor which increases its size.
2. Steam turbines require more capital and running cost as compared to gas turbine.
3. There is no need of water in a gas turbine while boilers are operating for generation of steam which requires a mass storage of water.
4. For peak load and standby power generation gas turbines are more suitably used as compared to steam engine.
5. The floor area covered by the gas turbine is very less as compared to steam engine.
6. There is a 70 % weight reduction in case of gas turbine as compared to steam engine.
7. Gas turbine requires cleaner and safer fuel which does not pollute the environment but steam engine produces gases which are dangerous for environment.

5.4. Classify the gas turbines.

Ans. Gas turbines are mainly of two types :

1. Constant pressure gas turbines :

(a) Open cycle constant pressure gas turbines

2. Constant volume gas turbines : Constant volume gas turbines are made first. But now a days it becomes obsolete because of use of valves and consequent intermittent operations. Now a days constant pressure gas turbines are used.

Open cycle gas turbines are mostly used in all fields. Closed cycle gas turbines are used because it can burn cheap fuel. Now a days price of fuel oils are rising hence use of closed cycle gas turbine becomes necessary for running the plant at low cost.

5.5. Explain Joule or Brayton cycle in detail and provide its p - V and T - s diagram.

OR

Derive the expression for thermal efficiency of a simple gas turbine plant.

Ans. **Brayton cycle or Joule cycle :** It is theoretical cycle for gas turbines. It is also known as constant pressure cycle for a perfect gas. The basic components of a Brayton cycle are shown in Fig. 5.2(a).

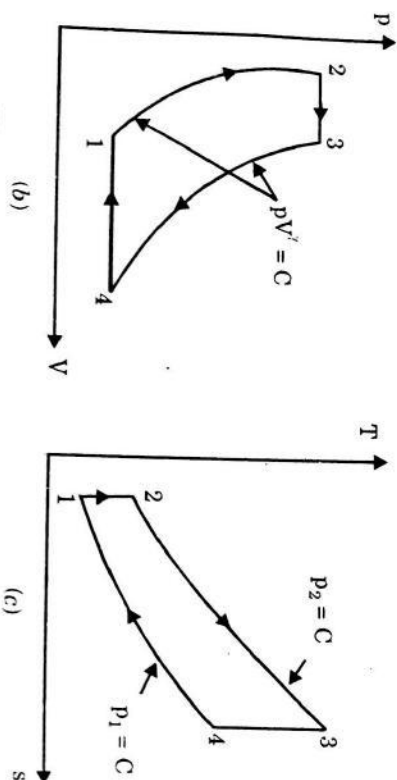
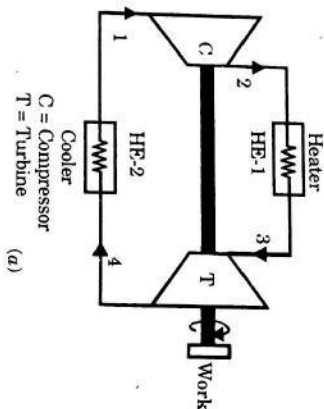


Fig. 5.2 Brayton cycle : (a) Basic components of a gas turbine power plant (b) p - V diagram (c) T - s diagram.

The components are compressor, heat exchanger, turbine and cooler.

There occur two isentropic processes and two constant pressure processes. Compression and expansion of working fluid is done by isentropic process while addition and rejection of heat is done at constant pressure. In Fig. 5.2, we see the p - V and T - s curve for the cycle.

Process 1-2 : Air is being compressed isentropically by compressor between the pressure range p_1 to p_2 .

Process 2-3 : It is constant pressure heat addition process. In this process temperature increases from T_2 to T_3 at constant pressure.

Process 3-4 : The air is expanded isentropically from pressure p_2 to p_1 and temperature drops from T_3 to T_4 .

Process 4-1 : It is constant pressure heat rejection process as temperature reduces from T_4 to T_1 .

Now, Work done per cycle = Heat added/cycle - Heat rejected/cycle

Heat addition in process 2-3 = $m C_p (T_3 - T_2)$

Heat rejected in process 4-1 = $m C_p (T_4 - T_1)$

Work done per cycle = $m C_p (T_3 - T_2) - m C_p (T_4 - T_1)$

$\eta_{\text{air-standard}} = \frac{\text{Work done / cycle}}{\text{Heat addition / cycle}}$

$$\eta_{\text{air-standard}} = \frac{m C_p (T_3 - T_2) - m C_p (T_4 - T_1)}{m C_p (T_3 - T_2)}$$

$$\eta_{\text{air-standard}} = 1 - \frac{T_4 - T_1}{T_3 - T_2}$$

From process 1-2,

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1} \right)^{\frac{\gamma-1}{\gamma}}$$

$$\frac{p_2}{p_1} = r_p = \text{pressure ratio}$$

$$T_2 = T_1 (r_p)^{\frac{\gamma-1}{\gamma}}$$

Similarly, from process 3-4,

$$T_3 = T_4 (r_p)^{\frac{\gamma-1}{\gamma}}$$

Putting the values of T_2 and T_3 in equation (i), we get

$$\begin{aligned} \eta_{\text{air-standard}} &= 1 - \frac{T_4 - T_1}{T_4 (r_p)^{\frac{\gamma-1}{\gamma}} - T_1 (r_p)^{\frac{\gamma-1}{\gamma}}} \\ &= 1 - \frac{1}{(r_p)^{\frac{\gamma-1}{\gamma}}} \end{aligned} \quad \dots (ii)$$

The equation (ii) shows that the efficiency of the ideal Joule cycle increases with the pressure ratio.

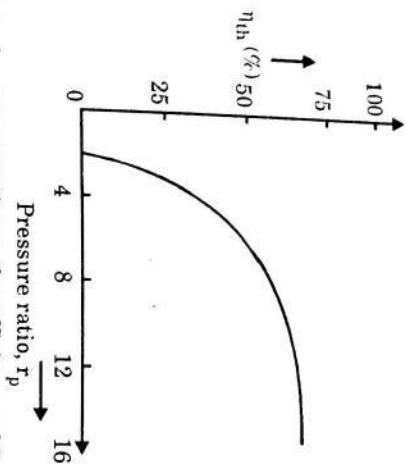


Fig. 5.3. Effect of pressure ratio on the efficiency of Brayton cycle.

5.6. Discuss with the help of graph, the variation of specific output with pressure ratio at various maximum cycle temperatures for a gas turbine plant.

OR

[UPTU 2006-07, Marks 05]

Prove that the pressure ratio for maximum work is given by

$$r_p = \left(\frac{T_3}{T_1} \right)^{\frac{\gamma}{2(\gamma-1)}}$$

Ans. Work done per cycle = Heat added/cycle – Heat rejected/cycle
 $= mC_p (T_3 - T_2) - mC_p (T_4 - T_1)$
 $= mC_p (T_3 - T_4) - mC_p (T_2 - T_1)$
 $= mC_p \left[T_3 \left(1 - \frac{T_4}{T_3} \right) - T_1 \left(\frac{T_2}{T_1} - 1 \right) \right]$

Here we refer T_1 as the minimum temperature and T_3 as the maximum temperature for the cycle. As we know that

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

Let us consider $\frac{\gamma-1}{\gamma} = z$

$$\text{Work done per cycle, } W = mC_p \left[T_3 \left(1 - \frac{1}{(r_p)^z} \right) - T_1 (r_p^z - 1) \right]$$

For maximum work done differentiate the above equation w.r.t pressure ratio r_p ,

$$\frac{dW}{dr_p} = mC_p \left[T_3 \frac{z}{(r_p)^{z+1}} - T_1 z (r_p)^{z-1} \right]$$

For maximum work done,

$$\frac{dW}{dr_p} = 0$$

$$mC_p \left[T_3 \frac{z}{(r_p)^{z+1}} - T_1 z (r_p)^{z-1} \right] = 0$$

$$\frac{T_3}{(r_p)^{z+1}} = T_1 (r_p)^{z-1}$$

$$(r_p)^{2z} = \frac{T_3}{T_1}$$

$$r_p = \left(\frac{T_3}{T_1} \right)^{\frac{1}{2z}}$$

$$r_p = \left(\frac{T_3}{T_1} \right)^{\frac{\gamma}{2(\gamma-1)}}$$

Thus, the pressure ratio for maximum work is given by the above expression. The variation of specific output with pressure ratio at various maximum cycle temperatures is shown in Fig. 5.4.

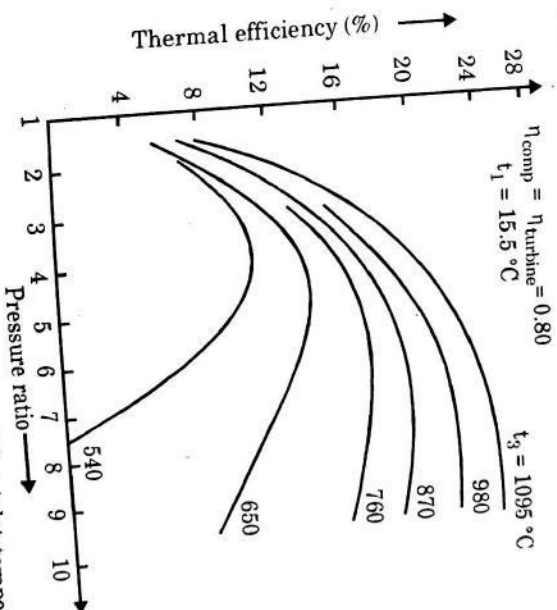


Fig. 5.4. Effect of pressure ratio and turbine inlet temperature.

5.7. Define the term 'work ratio'.

Ans. Work ratio is defined as the ratio of net work output to the work done by the turbine.

$$\text{Work ratio} = \frac{W_r - W_c}{W_r}$$

where, W_r = work done by turbine = $mC_p(T_3 - T_4)$, and W_c = work done by compressor = $mC_p(T_2 - T_1)$.

$$\text{Work ratio} = \frac{mC_p(T_3 - T_4) - mC_p(T_2 - T_1)}{mC_p(T_3 - T_4)}$$

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

Putting the values of T_2 and T_4 as,

$$T_2 = T_1(r_p)^\gamma \quad \text{and} \quad T_4 = T_3 \cdot \frac{1}{(r_p)^\gamma}$$

$$\text{Work ratio} = 1 - \frac{T_1}{T_3} \left[\frac{(r_p)^\gamma - 1}{1 - (r_p)^\gamma} \right]^{\frac{\gamma-1}{\gamma}}$$

$$= 1 - \frac{T_1}{T_3} (r_p)^{\frac{\gamma-1}{\gamma}}$$

5.8. A power plant operating on Joule cycle has a pressure ratio of 6 to 1. The maximum and minimum temperatures are 1000 °C and 20 °C respectively. Calculate (a) the air standard efficiency (b) the specific output. Given $\gamma = 1.4$ and $c_p = 1.005 \text{ kJ/kg-K}$.

Ans. Given : Pressure ratio,

$$\frac{P_2}{P_1} = \frac{6}{1} = r_p$$

Maximum temperature, $T_3 = 1000 + 273 = 1273 \text{ K}$

Minimum temperature, $T_1 = 20 + 273 = 293 \text{ K}$

(a) The air standard efficiency,

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

$$= 1 - \frac{1}{(6)^{(1.4-1)/1.4}} = 0.40$$

$\eta = 40\%$

(b) Specific output = $c_p(T_3 - T_4) - c_p(T_2 - T_1)$

= Work done by turbine - Work done by compressor

$$\text{We have, } \frac{T_3}{T_4} = \frac{T_2}{T_1} = (r_p)^{\frac{\gamma-1}{\gamma}}$$

$$\frac{1273}{293} = \frac{T_2}{T_1} = (6)^{\frac{1.4}{1.4}}$$

$\Rightarrow T_2 = 762.96 \approx 763 \text{ K}$

And, $T_2 = 488.87 \approx 489 \text{ K}$

So, specific output

$$= 1.005 [(1273 - 763) - (489 - 293)]$$

$$= 315.57 \text{ kJ/kg}$$

5.9. Show that for maximum work output from a gas turbine working on Brayton cycle T_2 should be equal to T_1 .

Ans. Consider the expression of pressure ratio for maximum work output given as

$$r_p = \left(\frac{T_3}{T_1} \right)^{\frac{1}{2(\gamma-1)}} \quad \dots (i)$$

$$\text{As we know } (r_p)^{\frac{\gamma-1}{\gamma}} = \frac{T_3}{T_4} = \frac{T_2}{T_1}$$

$$T_1 \cdot T_3 = T_4 \cdot T_2 \quad \dots (ii)$$

$$\text{and } r_p = \left(\frac{T_3}{T_4} \right)^{\frac{1}{(\gamma-1)}} \quad \dots (iii)$$

Put the value of r_p in equation (i), we get

$$\left(\frac{T_3}{T_4} \right)^{\frac{\gamma}{(\gamma-1)}} = \left(\frac{T_3}{T_1} \right)^{\frac{1}{2(\gamma-1)}}$$

$$\frac{T_3}{T_4} = \left(\frac{T_3}{T_1} \right)^{\frac{1}{2}}$$

$$T_4 = (T_1 \cdot T_3)^{1/2}$$

Put the value of T_4 from equation (ii),

$$T_4 = (T_1 \cdot T_3)^{1/2}$$

$\Rightarrow$

$$T_4 = T_2$$

Hence, for maximum work output from a gas turbine working on Brayton cycle T_2 should be equal to T_1 .

5.10. With neat sketch explain the constant volume combustion turbine.

Ans.

Constant volume combustion turbine: In a constant volume combustion turbine the air is sucked by compressor 'C' from the atmosphere and after the compression process this air is fed into the combustion chamber 'D' using the valve 'V'. Before the air enters into combustion chamber, it was filled by fuel using a fuel pump 'P'. This mixture of compressed air and fuel is burnt by use of a spark plug 'S'. The combustion of fuel is done at constant pressure

and the gases after the burning of fuel are entered into the turbine using valve V_2 . These gases drive the turbine to produce useful work and then get exhaust to the atmosphere. This process occurs repeatedly.

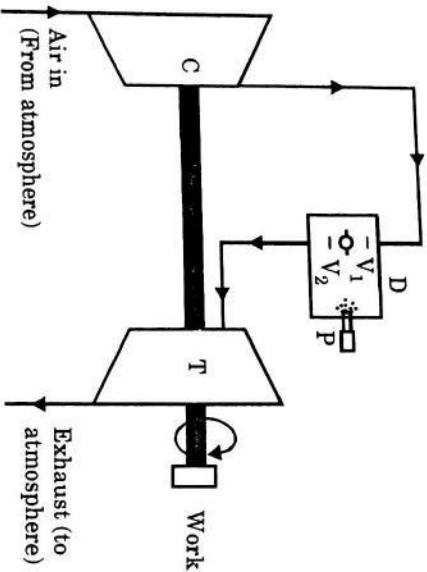


Fig. 5.5. Constant volume combustion gas turbine.

5.11. With neat sketches explain the working of a simple constant pressure open cycle gas turbine and closed gas turbine.

Ans. Constant pressure open cycle gas turbine :

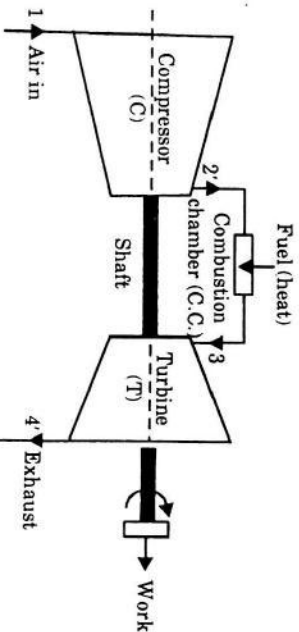


Fig. 5.6. Open cycle gas turbine.

In open cycle, a rotary compressor and a turbine are mounted on a common shaft. Air is drawn into the compressor and then compressed air is drawn into the combustion chamber. Here energy is supplied by the spraying fuel into the air stream. After that hot gases expand through the turbine and exhaust to the atmosphere. **Constant pressure closed gas turbine cycle :** As shown in Fig. 5.7 open cycle and closed cycle are same in all manner, except

in closed cycle after the exhaust air is sent to a cooling medium it can be further used by the compressor.

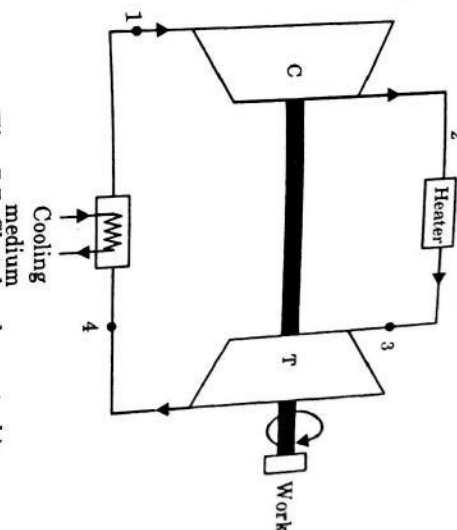


Fig. 5.7. Closed cycle gas turbine.

CONCEPT OUTLINE 2

Methods of improvement of thermal efficiency of open cycle gas turbine plant : Following methods are used to increase the specific output and thermal efficiency of the plant :

- Intercooling
- Reheating
- Regeneration.

Stage efficiency : $\eta_{\text{stage}} = \frac{\text{Work done on shaft/stage}}{\text{Adiabatic heat drop/stage}}$

Polytropic efficiency : $\eta_p = \frac{T_2 - T_1}{T_2' - T_1}$

5.12. What are the various methods for improvement of thermal efficiency of an open cycle gas turbine ?

OR

Draw schematic and T-s diagrams of an open cycle gas turbine plant which has been provided with perfect intercooling, reheating and regeneration arrangement. [UPTU 2007-08, Marks 10]

OR

Explain in brief the various methods of improving the efficiency of a gas turbine working on a simple Brayton cycle with the help of neat sketches. [UPTU 2008-09, Marks 10]

OR

Explain in brief the different methods adopted for improving the efficiency of open cycle gas turbines.

[UPTU 2002-03, Marks 05]

OR

Show the influence of reheating and regeneration on performance of gas turbine cycle.

[UPTU 2009-10, Marks 05]

OR

Discuss the effect of intercooling and regeneration on the performance of Brayton Cycle. [UPTU 2010-11, Marks 05]

OR

How regeneration in gas turbine increases thermal efficiency of the plant?

OR

Discuss the effect of reheating, regeneration and intercooling on the performance of gas turbine with neat schematic and $T-s$ chart.

[UPTU 2012-13, Marks 10]

Ans. Thermal efficiency or specific output of an open cycle gas turbine can be improved by following three methods:

- (i) **Intercooling:** This is required to reduce the compressor work and to increase the work ratio. The compression of air is to be done in two compressors. Firstly in low pressure compressor then in high pressure compressor, compression process is to be done. An intercooler is used in between the two compressors.

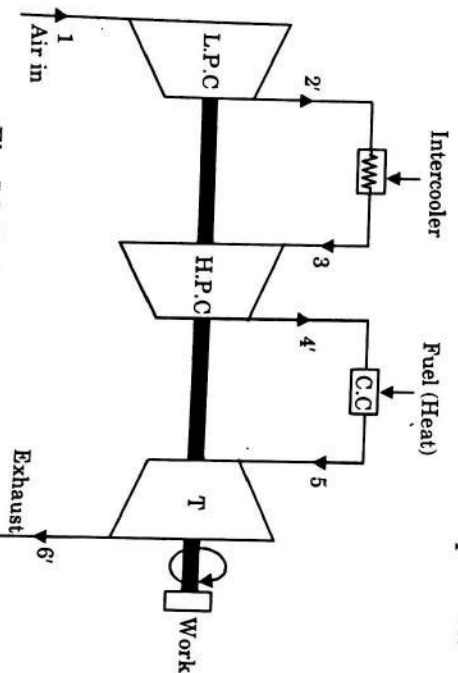


Fig. 5.8. Turbine plant with intercooler.

Fig. 5.9 shows ideal and actual processes which occur in an open cycle gas turbine. The dotted lines show the actual curve and the thicker one shows the ideal curve.

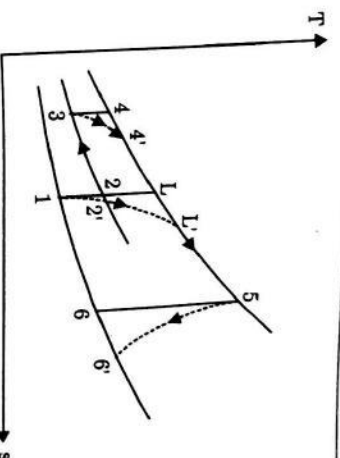


Fig. 5.9. $T-s$ diagram for the unit.

From $T-s$ diagram,

The process with intercooling is 1-2-3-4-5-6 (Ideal process) or 1-2'-3-4'-5-6' (Actual process).

The work required to run the compressor with intercooling is

For ideal condition, $W_{ci} = C_p (T_2 - T_1) + C_p (T_4 - T_3)$

For actual condition, $W_{ca} = C_p (T_2' - T_1) + C_p (T_4' - T_3)$

The process 1-L-5-6 is ideal process without intercooling.

whereas 1-L'-5-6' is actual process without intercooling.

The work required to run the compressor without intercooling is

For ideal condition, $W_{ci} = C_p (T_L - T_1)$

For actual condition, $W_{ca} = C_p (T_L' - T_1)$

$= C_p (T_L - T_2 + T_2 - T_1)$

$= C_p (T_L - T_2) + C_p (T_2 - T_1)$

For actual condition, $W_{ca} = C_p (T_L' - T_1)$

$= C_p (T_L' - T_2' + T_2' - T_1)$

$= C_p (T_L' - T_2') + C_p (T_2' - T_1)$

$= C_p (T_L' - T_2') + C_p (T_2' - T_1)$

On comparing both the work done it can be concluded that the work input with intercooling is less than the work input without intercooling. As it is clear from the $T-s$ curve that

$T_2' - T_1' > T_2 - T_1$ (for actual process)

and, $T_L' - T_2' > T_L - T_2$ (for ideal process)

But the heat supplied increases and this increase in heat supply leads to decrement in thermal efficiency.

Reheating: It is done to improve the output from turbine. This process uses two turbines a high pressure turbine and a low pressure turbine. There is a reheater present in between these two turbines.

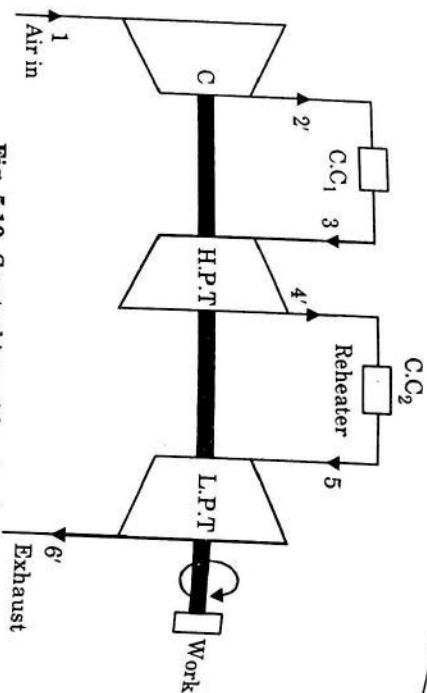


Fig. 5.10. Gas turbine with reheater.

Here high pressure turbine is used to drive the compressor and the low pressure turbine provides useful work output.

Actual process is shown by 1-2'-3-4'-5-6' (with reheating)

Ideal process is shown by 1-2-3-4-5-6 (with reheating)

Actual process without reheating is shown by 1-2'-3-L' and the ideal process without reheating is shown by 1-2-3-4-L.

$$= C_p (T_5' - T_6')$$

The work output without reheating
 $= C_p (T_4' - T_L')$

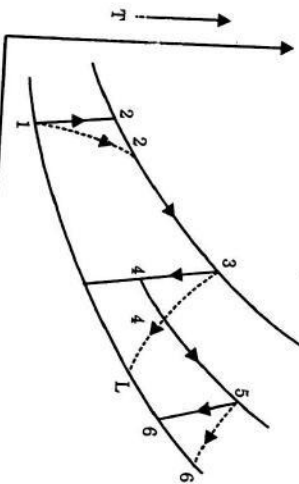


Fig. 5.11. T-s diagram for reheater.

From T-s diagram it is clear that

$$T_5' - T_6' > T_4' - T_L'$$

Hence the work output increases with reheating. This will also increase the work input and it may result into reduction in thermal efficiency.

(iii) **Regeneration:** This is a process that uses the heat of exhaust gases to reduce the heat supply in combustion chamber. Here the heat of exhaust gases is used to increase the temperature of the compressed air with use of a heat exchanger.

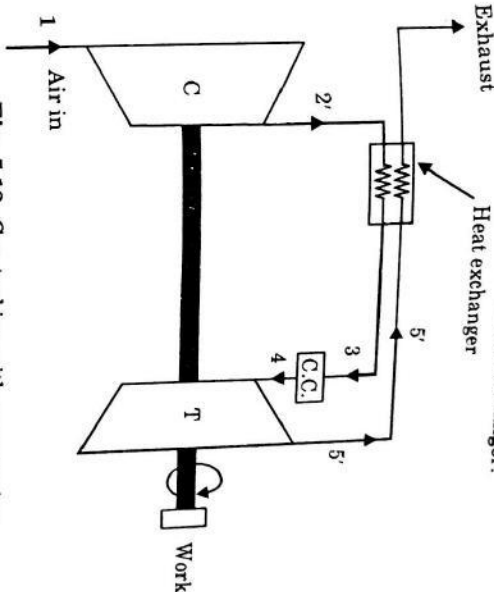


Fig. 5.12. Gas turbine with regenerator.

In T-s diagram, process 2-3 represents the heat flow into the compressed air through heat exchanger and 3-4 shows the heat supplied for combustion of fuel.

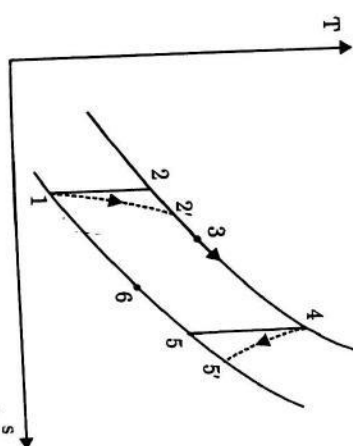


Fig. 5.13. T-s diagram for the unit.

The effectiveness of heat exchanger is given by,

$$\epsilon = \frac{\text{Increase in enthalpy per kg of air}}{\text{Available increase in enthalpy per kg of air}} = \frac{T_3 - T_2'}{T_5' - T_2'}$$

5.13. Obtain optimum pressure ratio condition for minimum compressor work requirement in two stage perfect intercooled compression. [UPVTU 2009-10, Marks 05]

Ans. Perfect intercooling occurs when the temperature at inlet to subsequent stages of compression is reduced to ambient temperature.

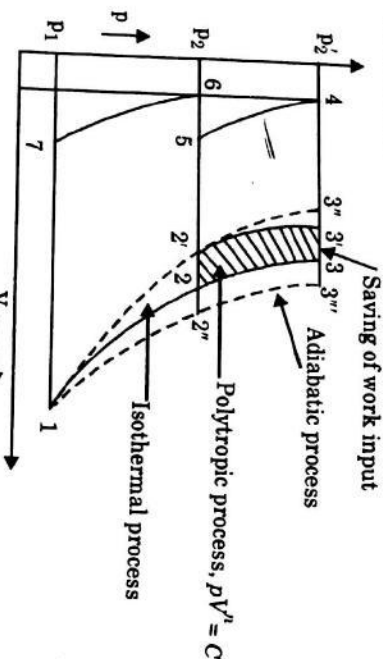


Fig. 5.14. Multistage compression with intercooling.

Intercooling between two stages causes temperature drop from 2 to 2', i.e., discharge from first stage (at 2) is cooled up to the ambient temperature state (at 2') which lies on isothermal compression process 1-2'-3'. Intercooling offers reduced work requirement by the amount shown by area 22'33 on p-V diagram.

Assumptions: Following assumptions are made for analysis of multistage (or two stage) compressor:

1. Suction and delivery pressure should be constant. Compression follows same index of compression in every stage.
2. Intercooling should be perfect between compression stages.
3. Mass of air in low pressure stage and high pressure stage should be same.
4. Air behaves as perfect gas during compression.

From p-V diagram, the compressor work requirement can be given as:

Work requirement in LP cylinder,

$$W_{LP} = \left(\frac{n}{n-1} \right) p_1 v_1 \left[\left\{ \frac{p_2}{p_1} \right\}^{\frac{n-1}{n}} - 1 \right]$$

Work requirement in HP cylinder,

$$W_{HP} = \left(\frac{n}{n-1} \right) p_1 v_1 \left[\left\{ \frac{p_2}{p_1} \right\}^{\frac{n-1}{n}} - 1 \right]$$

For perfect intercooling,

$$p_1 v_1 = p_2 v_2$$

$$W_{HP} = \left(\frac{n}{n-1} \right) p_2 v_2 \left[\left\{ \frac{p_2}{p_2} \right\}^{\frac{n-1}{n}} - 1 \right]$$

Total work requirement for intercooling,

$$W_C = W_{LP} + W_{HP}$$

$$= \frac{n}{n-1} p_1 v_1 \left[\left\{ \frac{p_2}{p_1} \right\}^{\frac{n-1}{n}} - 1 \right] + p_2 v_2 \left[\left\{ \frac{p_2}{p_1} \right\}^{\frac{n-1}{n}} - 1 \right]$$

$$W_C = \frac{n}{n-1} p_1 v_1 \left[\left\{ \frac{p_2}{p_1} \right\}^{\frac{n-1}{n}} + \left\{ \frac{p_2}{p_1} \right\}^{\frac{n-1}{n}} - 2 \right]$$

$$\text{Power required} = \frac{W_C \times N}{75 \times 60} \text{ HP}$$

The compressor work can be optimized with respect to intermediate pressure p_2 . Differentiate W_C with respect to p_2 (intermediate pressure).

$$\frac{dW_C}{dp_2} = \frac{d}{dp_2} \left[\left(\frac{n}{n-1} \right) p_1 v_1 \left\{ \left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} + \left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 2 \right\} \right]$$

$$= \left(\frac{n}{n-1} \right) p_1 v_1 \frac{d}{dp_2} \left\{ \left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} + \left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 2 \right\}$$

$$\frac{dW_C}{dp_2} = \left(\frac{n}{n-1} \right) p_1 v_1 \left[\frac{n-1}{n} \cdot \frac{1}{p_1} \cdot p_1^{\frac{1-n}{n}} \cdot p_2^{\frac{n-1}{n}} - \left(\frac{n-1}{n} \right) \left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} \cdot p_2^{\frac{1-2n}{n}} \right]$$

For minimum value of compressor work,

$$\frac{dW_C}{dp_2} = 0$$

$$\frac{1-n}{n} \cdot p_2^{\frac{n-1}{n}} = \left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} \cdot p_2^{\frac{1-2n}{n}}$$

$$p_1^{\frac{n-1}{n}} \cdot p_2^{\frac{n-1}{n}} = \left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} \cdot p_1^{\frac{n-1}{n}}$$

$$p_2^{\frac{n-1}{n}} = p_1^{\frac{n-1}{n}} \cdot p_1^{\frac{n-1}{n}}$$

$$p_2^{\frac{n-1}{n}} = p_1^{\frac{n-1}{n}}$$

Thus, for minimum compressor work requirement pressure ratio in each stage is equal.

5.14. Discuss the effect of regenerator on the performance of gas turbine cycle. When regenerator becomes superfluous?

Ans.

For the maximization of specific work output the gas turbine exhaust temperature should be equal to compressor exhaust temperature. The turbine exhaust temperature is normally much above the ambient temperature. Thus, there exist potential for tapping the heat energy getting lost to surroundings with exhaust gases. Here it is devised to use this potential by means of a heat exchanger called regenerator, which shall preheat the air leaving compressor before entering the combustion chamber, thereby reducing the amount of fuel to be burnt inside combustion chamber (combustor).

Regenerative air standard gas turbine cycle shown in Fig. 5.15, has a regenerator (counter flow heat exchanger) through which the hot turbine exhaust gas and comparatively cooler air coming from compressor flow in opposite directions. Under ideal conditions, no frictional pressure drop occurs in either fluid stream while turbine exhaust gas gets cooled from 4 to 4' while compressed air is heated from 2 to 2'. Assuming regenerator effectiveness as 100 % the temperature rise from 2 to 2' and drop from 4 to 4' is shown on T-s diagram.

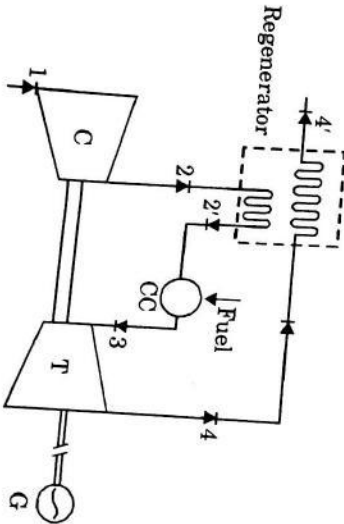
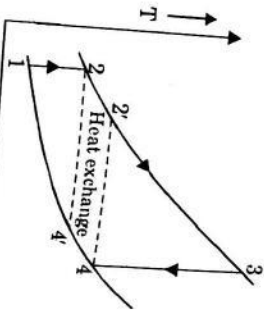


Fig. 5.15. Regenerator air standard gas turbine cycle.



Regenerator effectiveness, $\epsilon = \frac{h_2' - h_2}{h_1' - h_2}$, where 'h' refers to specific enthalpy values.

Thus, thermodynamically the amount of heat now added shall be $Q_{add, regen} = m(h_3 - h_2')$

whereas without regenerator the heat added, $Q_{add} = m(h_3 - h_2)$

Here it is obvious that, $Q_{add, regen} < Q_{add}$.

This shows an obvious improvement in cycle thermal efficiency. Net work produced per unit mass flow is not altered by the use of regenerator.

Air standard cycle thermal efficiency,

$$\eta_{regen} = \frac{(h_3 - h_2) - (h_2 - h_1)}{(h_3 - h_2)}$$

$$\eta_{regen} = \frac{c_p(T_3 - T_1) - c_p(T_2 - T_1)}{c_p(T_3 - T_1)}$$

Thus, regenerative gas turbine cycle efficiency approaches to Carnot cycle efficiency at $r = 1$ which is because in this limiting situation the Carnot cycle requirement of total heat addition and rejection at maximum and minimum cycle temperature is satisfied. Variation of efficiency with cycle pressure ratio for regenerative cycle is shown in Fig. 5.16, for fixed γ values.

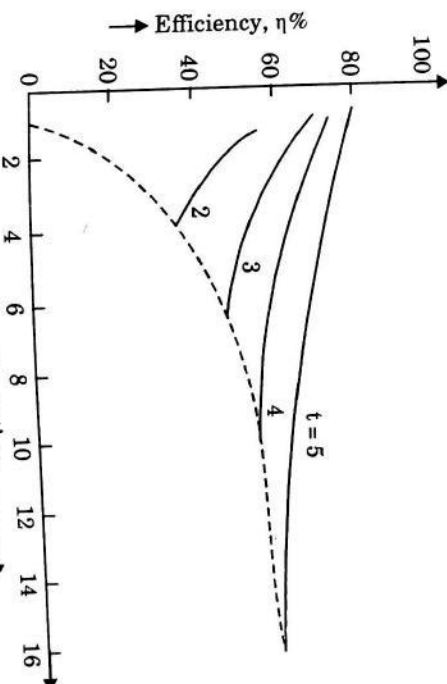


Fig. 5.16. Efficiency vs. pressure ratio for regenerative gas turbine cycle.

Cycle efficiency is seen to decrease with increasing pressure ratio till pressure ratio becomes equal to $r = \gamma^{(\gamma-1)/2\gamma}$. In earlier discussion it has been shown that at this pressure ratio value of the specific work output becomes maximum. Same specific work output

variation is true for this case too. For further higher values of pressure ratio the heat exchanger shall cool the air leaving compressor and lower the cycle efficiency than simple cycle efficiency.

This is because of which the constant ' r ' lines are not extended beyond the point where they meet efficiency curve for simple cycle.

Thus, it can be concluded that for getting improvement in efficiency by incorporating regenerator the pressure ratio ' r ' appreciably less than the optimum one for maximum specific work output should be used. Also maximum turbine inlet temperature should be used.

For ideal heat exchange in regenerator with 100 % effectiveness, Upon substitution it yields $T_2' = T_4$

$$\eta'_{\text{regen}} = \frac{(T_3 - T_4) - (T_2' - T_1)}{(T_3 - T_4)}$$

$$\eta'_{\text{regen}} = 1 - \frac{(T_2' - T_1)}{(T_3 - T_4)}$$

From thermodynamic processes,

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

$$\text{or } \frac{T_2 - T_1}{T_3 - T_4} = \frac{T_1}{T_4}$$

$$\text{or } \frac{T_2 - T_1}{T_3 - T_4} = \frac{T_1}{T_4} \times \frac{T_3}{T_4}$$

The use of regenerator is only recommended when the exit temperature of the turbine gases is much above the ambient temperature. But if the temperature is below the ambient temperature then the use of regenerator is unnecessary, i.e., regenerator is become superfluous.

5.15. Name the operating variables which affect the thermal efficiency of open cycle gas turbine.

Ans. There are some variables which affect the thermal efficiency of open cycle gas turbine.

- (i) **Pressure ratio (r_p)** : For other variables being constant as pressure ratio increases thermal efficiency also increase and this will lead to an optimum pressure ratio at which thermal efficiency is maximum. Before and after this pressure ratio thermal efficiency decreases.

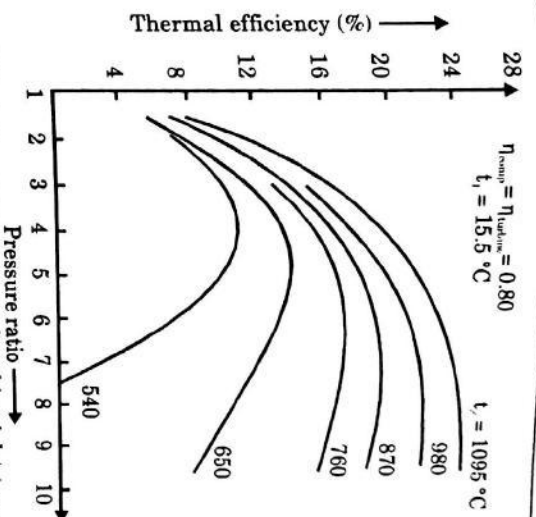


Fig. 5.17. Effect of pressure ratio and turbine inlet temperature.

- (ii) **Turbine inlet temperature (T_3)** : Up to a certain limit, increase in turbine inlet temperature (T_3) will increase the thermal efficiency of the open cycle gas turbine. But this temperature will depend upon the blade material of a turbine.

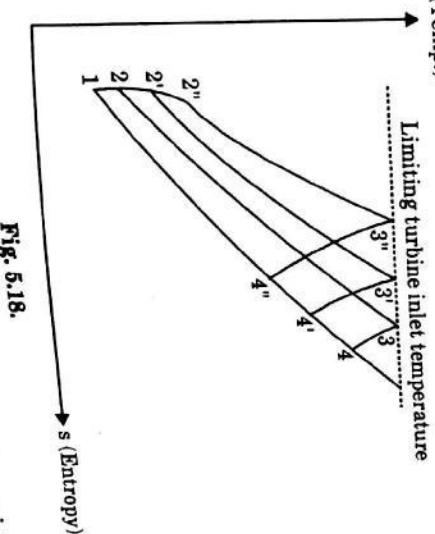


Fig. 5.18.

- (iii) **Compressor inlet temperature (T_1)** : For other variables being constant, if we decrease the compressor inlet temperature this will improve the thermal efficiency of cycle.

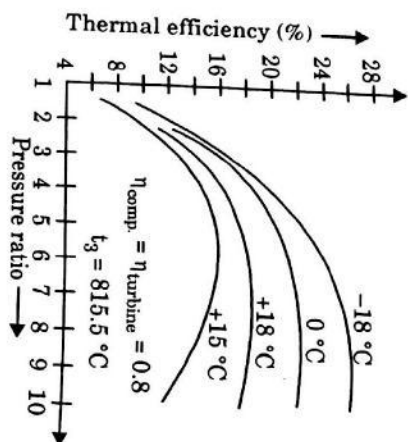


Fig. 5.19.

(iv) **Efficiencies of turbine and compressor :** There should be a proper and suitable combination of efficiencies for turbine and compressor, so that an efficient pressure ratio can be achieved. This results in increased thermal efficiency.

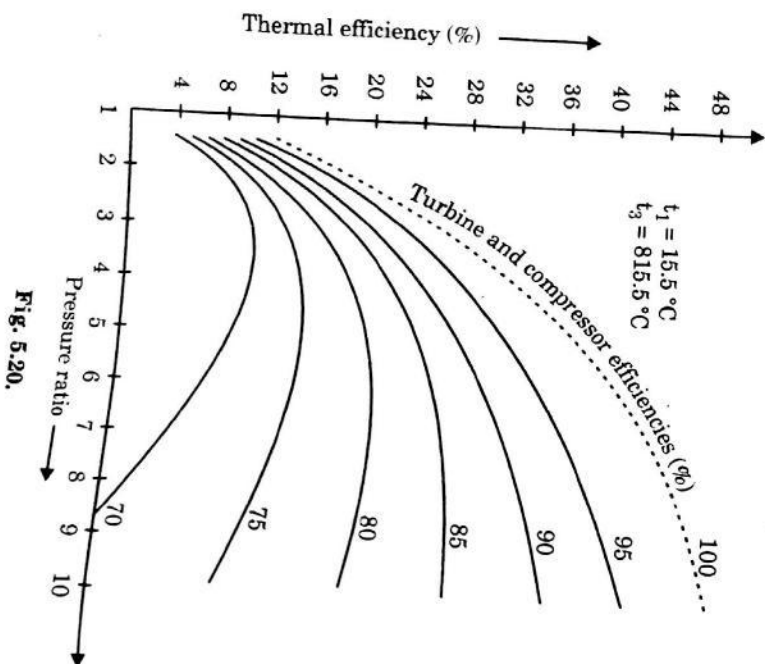


Fig. 5.20.

- 5.16. What do you understand by the following terms :
 (a) Stage efficiency
 (b) Polytropic efficiency.

OR

Define polytropic efficiency and its significance for turbine using its mathematical expression.

[UPTU 2009-10, Marks 05]

Ans.

(a) **Stage efficiency :** It is defined as the ratio of rate of work done and energy supplied to the stage. It can also be defined as the ratio of output of stage to the available energy for the stage.

$$\eta_{\text{stage}} = \frac{\text{Work done on shaft / stage}}{\text{Adiabatic heat drop / stage}}$$

It takes into account the aerodynamic losses in fixed and moving blade rows of the stage. It is defined for turbines and one stage consists of a pair of nozzle or fixed blades and moving blades.

(b) **Polytropic efficiency or small stage efficiency :** It is a value used to describe the efficiency of a compressor. A polytropic process is more difficult to analyze than a system under the isentropic or adiabatic assumptions. This difficulty arises from the fact that heat flows in and out of the system and this added energy changes some of the basic properties of the gas like the ratio of specific heats i.e., C_p and C_v . So, for a polytropic process, each new calculation requires a new value of C_p or C_v .

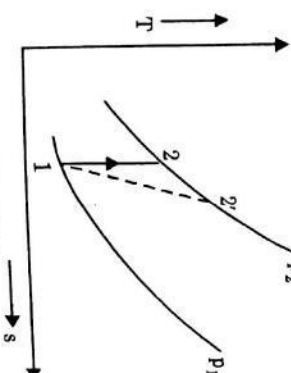


Fig. 5.21.

Polytropic efficiency is an alternative way of approaching isentropic efficiency. In this method, the compression process is supposed to be made up of many stages, each raising the pressure in a small amount.

Let us consider an ideal isentropic compression 1-2 and a real compression 1-2' occurs in a compressor. It is shown by the T-s curve. The pressure varies from P_1 to P_2 .

The polytropic efficiency or isentropic efficiency or small stage efficiency is

$$\eta_p = \frac{T_2 - T_1}{T_2 - T_1}$$

Relevance of polytropic efficiency : It may be applied to expansions as well as compressions. It may also be applied to expansions in nozzles.

In steam work, it is more usual to use the reheat factor which is based on the same principle.

5.17. Define stage efficiency for compressor stage. Also discuss its effect on overall performance of compressor.

Ans. Stage efficiency: Refer Q. 5.16 (a).
[UPTU 2009-10, Marks 05]

Effect of stage efficiency on overall performance of compressor : When compression process is completed in more than one stage, efficiency comes into existence. In case of multistage compression, the compression in first stage occurs at low temperature and subsequent compression in following stages occurs at higher temperature. Higher the average temperature during compression results into larger work requirement compared to low temperature, so there would be low average temperature during compression.

To reduce compression work, the inlet air temperature to compressor can be reduced. In multistage compression some part of compressed air, leaving the first stage is cooled up to ambient air temperature in intercooler and then sent to subsequent cylinder for compression. The intercooler between the stages reduces the compression work.

5.18. A compressor draws in air at 223.3 K temperature and 0.265 bar pressure. The compression ratio is 6. The polytropic efficiency is 0.86. Determine the temperature after compression. Take γ for air is 1.4.

Ans. Given: $T_1 = 223.3 \text{ K}$, $p_1 = 0.265 \text{ bar}$, $r_p = 6$, $\eta_p = 0.86$
For polytropic process

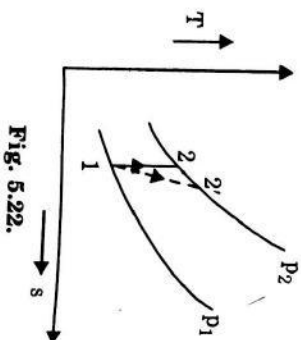


Fig. 5.22.

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1} \right)^{\frac{(\gamma-1)}{\gamma \eta_p}}$$

$$T_2 = 223.3(6)^{\frac{1.4-1}{1.4 \times 0.86}}$$

$$T_2 = 405 \text{ K}$$

5.19. A compressor draws in air at 15 °C and 0.3 bar. The air is compressed to 1.6 bar with a polytropic efficiency of 0.86.

Determine the temperature and the isentropic efficiency.

Ans. Given: $T_1 = 15 + 273 = 288 \text{ K}$, $p_1 = 0.3 \text{ bar}$, $p_2 = 1.6 \text{ bar}$
 $\eta_p = 0.86$

We know that for a polytropic process 1-2,

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1} \right)^{\frac{(\gamma-1)}{\gamma \eta_p}}$$

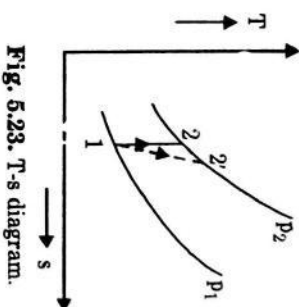


Fig. 5.23. T-s diagram.

$$T_2 = 288 \left(\frac{1.6}{0.3} \right)^{\frac{1.4-1}{1.4 \times 0.86}}$$

$$T_2 = 502.25 \text{ K}$$

Now, for isentropic process 1-2,

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1} \right)^{\frac{(\gamma-1)}{\gamma}}$$

$$T_2 = 288 \left(\frac{1.6}{0.3} \right)^{\frac{1.4-1}{1.4}}$$

$$T_2 = 464.63 \text{ K}$$

$$\eta_{\text{isentropic}} = \frac{T_2 - T_1}{T_2 - T_1} = \frac{464.63 - 288}{502.25 - 288} = 0.8244 \text{ or } 82.44 \%$$

5.20. What are the different factors which cause the difference between an ideal cycle and real cycle of a gas turbine ?

Define polytropic efficiency and its relevance.

IUPTU 2006-07, Marks 05]

OR

Describe about the real gas turbine cycles.

OR

Discuss with neat sketch and graph the deviation of actual gas turbine cycle from ideal cycles.

Ans. Real gas turbine cycle : The ideal cycle is not possible because of following reasons :

- The efficiency of turbines and compressors are not 100% so there is a deviation in expansion and compression processes.
- There is also a change in kinetic energy occurs and due to high velocity fluid there is friction between the air molecules and between the air and the casing. This will cause heating and it leads to increase in entropy during compression and expansion process.

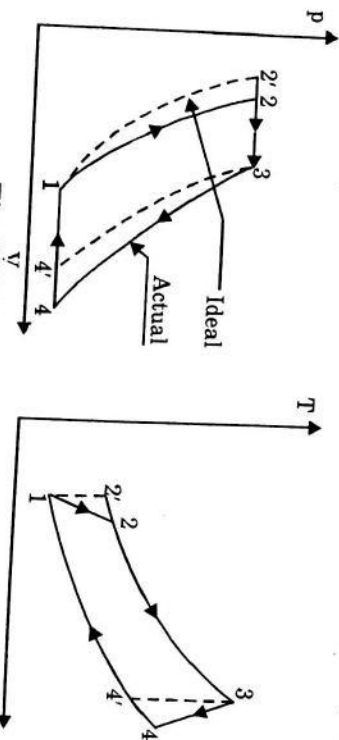


Fig. 5.24. Real gas turbine cycle.

From Fig. 5.24,

Isentropic efficiency of compressor

$$\eta_c = \frac{\text{Isentropic work}}{\text{Actual work}}$$

$$\eta_c = \frac{C_p(T_2 - T_1)}{C_p(T_2' - T_1)}$$

$$\eta_c = \frac{T_2 - T_1}{T_2' - T_1}$$

Isentropic efficiency of turbine

$$\eta_t = \frac{\text{Actual work}}{\text{Isentropic work}}$$

$$\eta_t = \frac{C_p(T_3 - T_4)}{C_p(T_3 - T_4')}$$

- There is also a pressure drop occur in the combustion chamber due to fluid friction and this will leads to

$$\frac{P_3}{P_1} < \frac{P_2}{P_1}$$

- The values of C_p and C_v are not constant because of change of temperature and chemical compositions of gases mixture.

For polytropic efficiency and its relevance : Refer Q. 5.16(b)

- In a gas turbine plant, operating on Joule cycle, air is compressed at 1 bar and 15 °C through a pressure ratio of 6. It is then heated to 1000 K in a combustion chamber and expanded back to a pressure of 1 bar. Calculate the work done, cycle efficiency, and work ratio. Assume isentropic efficiencies of the turbine and compressor are 90 and 85 percent respectively.

Ans.

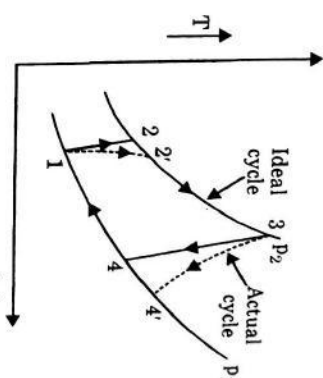


Fig. 5.25. T-s diagram.

Given : $P_1 = 1$ bar, $T_1 = 15 + 273 = 288$ K, $T_3 = 1000$ K

$r_p = 6$, $\eta_T = 90\%$ and $\eta_c = 85\%$

$\gamma = 1.4$ for air

As

$$r_p = 6$$

$$\frac{P_2}{P_1} = 6 = \frac{P_3}{P_4}$$

$$P_2 = 6P_1 = 6 \times 1$$

$$= 6 \text{ bar}$$

For compressor, process 1-2 and 1-2'

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}}$$

$$T_2 = 288 \times 6^{\frac{1.4-1}{1.4}}$$

$$T_2 = 480.53 \text{ K}$$

$$\eta_c = \frac{T_2 - T_1}{T_2 - T_1}$$

$$0.85 = \frac{480.53 - 288}{T_2 - 288}$$

$$T_2' = 514.50 \text{ K}$$

For turbine, process 3-4 and 3-4'

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4} \right)^{\frac{\gamma-1}{\gamma}}$$

$$T_4 = 1000 \left(\frac{1}{6} \right)^{\frac{1.4-1}{1.4}} = 599.34 \text{ K}$$

$$\eta_T = \frac{T_3 - T_4}{T_3 - T_4'}$$

$$0.90 = \frac{1000 - T_4'}{1000 - 599.34}$$

$$T_4' = 639.406 \text{ K}$$

Work done = Turbine work - Compressor work

$$= C_p (T_3 - T_4) - C_p (T_2' - T_1)$$

$$= 1.005(1000 - 639.406) - 1.005(514.50 - 288)$$

$$= 134.76 \text{ kJ/kg}$$

$$\text{Heat supplied in process 2-3} = C_p (T_3 - T_2')$$

$$= 1.005(1000 - 514.50)$$

$$= 487.93 \text{ kJ/kg}$$

$$\text{Cycle efficiency} = \frac{\text{Work done or Work output}}{\text{Heat supplied}}$$

$$\text{Cycle efficiency} = \frac{134.76}{487.93}$$

$$= 0.276 \text{ or } 27.6\%$$

$$\text{Work ratio} = \frac{\text{Work output}}{\text{turbine output}}$$

$$= \frac{134.76}{1.005(1000 - 639.406)} = 0.37$$

- 5.22. Air at temperature of 15 °C enters a gas turbine plant working at pressure ratio of 6. Turbine inlet temperature is 800 °C. Isentropic efficiency of compression and expansion is 0.85 and calorific value of fuel used is 42 MJ/kg. Find thermal efficiency, air fuel ratio and specific fuel consumption of the gas turbine plant.

[UPTU 2010-11, Marks 10]

Gas Turbine and Jet Propulsion

213 (ME-4) B

Ans. Given :

Pressure ratio, $\frac{P_2}{P_1} = 5$

Inlet temperature, $T_1 = 15 + 273 = 288 \text{ K}$

Turbine inlet temperature, $T_3 = 800 + 273 = 1073 \text{ K}$

Calorific value of fuel, $CV = 42 \text{ MJ/kg}$

For air, $C_p = 1.005 \text{ kJ/kg} \cdot \text{K}$, $\gamma = 1.4$

$$\eta_{pc} = \eta_{pe} = 0.85$$

Polytropic efficiency is given as (for compression)

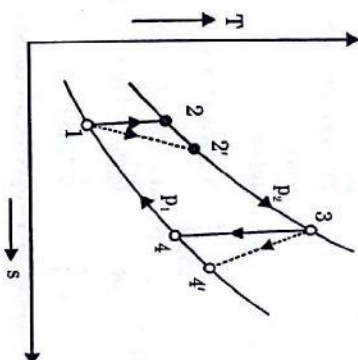


Fig. 5.26.

$$\eta_{pc} = \left(\frac{n}{n-1} \right) \left(\frac{\gamma-1}{\gamma} \right)$$

$$\left(\frac{n-1}{n} \right) = \left(\frac{\gamma-1}{\gamma} \right) \frac{1}{\eta_{pc}} \quad \dots (i)$$

Now, from gas law,

$$\frac{T_2'}{T_1} = \left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}}$$

From equation (i),

$$\frac{T_2'}{T_1} = \left(\frac{P_2}{P_1} \right)^{\left(\frac{\gamma-1}{\gamma} \right) \frac{1}{\eta_{pc}}}$$

$$T_2' = 288(5)^{0.4045 \times 1.4}$$

$$T_2' = 494.69 \text{ K}$$

Again polytropic process for expansion,

$$\frac{T_3}{T_4'} = \left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}}$$

$$= (5)^{0.4/0.85 \times 1.4}$$

$$= 1.718$$

$$T_4' = \frac{T_3}{1.718} = \frac{1073}{1.718} = 624.56 \text{ K}$$

Net workdone = Turbine work - Compressor work

$$= c_p (T_3 - T_4') - c_p (T_2' - T_1)$$

$$= 1.005[(1073 - 624.56) - (494.69 - 288)]$$

$$= 242.96 \text{ kJ/kg}$$

$$\text{Heat supplied} = c_p (T_3 - T_2')$$

$$= 1.005 (1073 - 494.69) = 581.20 \text{ kJ/kg}$$

$$\text{Thermal efficiency} = \frac{\text{Net work}}{\text{Heat supplied}}$$

$$= \frac{242.96}{581.20} = 0.418 = 41.8 \%$$

$$\text{Air-fuel ratio} = \frac{\text{External heat supplied in kJ/kg of air}}{\text{Calorific value of fuel in kJ/kg of fuel}}$$

$$= \frac{581.20}{42000} = 0.01383$$

$$\text{Specific fuel consumption} = \text{Specific air consumption} \times \text{Fuel air ratio}$$

$$= \frac{1}{\text{Specific output}} \times \text{Fuel air ratio}$$

$$= \frac{3600 \times 0.01383}{242.96} = 0.2049 \text{ kg/kW-h}$$

5.23. A simple gas turbine admits air at atmospheric pressure (1.013 bar) and 15 °C and compresses air in the compressor up to 16 bar. Then the air enters the combustion chamber and is heated to a maximum temperature of 1350 °C, turbine it enters the turbine and expands to atmospheric pressure. The isentropic efficiency of compressor and turbine is 0.87, combustion efficiency of compressor and at constant pressure for both air and gases is 1.005 kJ/kg·K. Ratio of specific heats 1.4. Determine the flow of air and gases for a net power of 200 MW developed.

Ans. Given: $P_1 = 1.013 \text{ bar}$, $P_2 = 16 \text{ bar}$, $P_3 = 16 - 0.3 = 15.7 \text{ bar}$
 $T_1 = 273 + 15 = 288 \text{ K}$, $T_3 = 1350 + 273 = 1623 \text{ K}$
 [UPTU 2011-12, Marks 10]

Gas Turbine and Jet Propulsion

215 (ME-4) B

$P_4 = 1.013 \text{ bar}$, $\eta_C = \eta_T = 0.87$, $\eta_{CC} = 0.98$
 For air and gases: $c_p = 1.005 \text{ kJ/kg·K}$

$\gamma = 1.4$

Power developed, $P = 200 \text{ MW}$

For isentropic compression 1-2,

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{16}{1.013} \right)^{\frac{1.4-1}{1.4}} = 2.2$$

$$T_2 = 2.2 \times 288 = 633.6 \text{ K}$$

Now,

$$\eta_C = \frac{T_2 - T_1}{T_2' - T_1} \Rightarrow 0.87 = \frac{633.6 - 288}{T_2' - 288}$$

$$T_2' = 685.24 \text{ K}$$

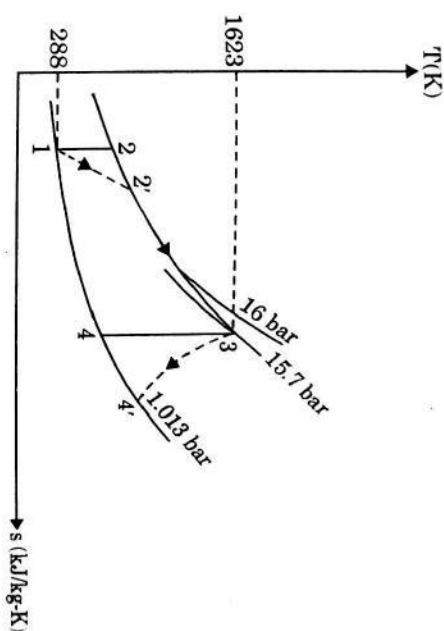


Fig. 5.27.

For isentropic expansion process 3-4,

$$\frac{T_4}{T_3} = \left(\frac{P_4}{P_3} \right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{1.013}{15.7} \right)^{\frac{1.4-1}{1.4}} = 0.46$$

$$T_4 = 1623 \times 0.46 = 746.58 \text{ K}$$

Now,

$$\eta_T = \frac{T_3 - T_4'}{T_3 - T_4}$$

$$0.87 = \frac{1623 - T_4'}{1623 - 746.58}$$

$$T_4' = 860.51 \text{ K}$$

$$W_C = c_p (T_2' - T_1) = 1.005 (685.24 - 288)$$

$$= 399.23 \text{ kJ/kg}$$

$$W_T = c_p (T_3 - T_4') = 1.005 (1623 - 860.51)$$

$$W_{\text{net}} = W_T - W_C$$

$$= 766.30 \text{ kJ/kg}$$

$$= 766.30 - 399.23 = 367.07 \text{ kJ/kg}$$

If the mass of air flowing is $\dot{m}_a$ kg/s, then the power developed by the plant is given by

$$P = \dot{m}_a \times W_{\text{net}} \text{ kW}$$

$$200 \times 10^3 = \dot{m}_a \times 367.07$$

$$\dot{m}_a = \frac{200 \times 10^3}{367.07}$$

$$\dot{m}_a = 544.86 \text{ kg/s}$$

5.24. Find the required air fuel ratio in a gas turbine whose turbine and compressor efficiencies are 85 % and 80 % respectively. Maximum cycle temperature is 875 °C. The working fluid can be taken as air which enters the compressor at 1 bar pressure and 27 °C. The pressure ratio is 4. Calorific value of fuel is 42,000 kJ/kg. There is a loss of 10 % of calorific value in the combustion chamber.

Ans. Given:

$$\eta_T = 85 \%, \eta_C = 80 \%$$

$$T_3 = 273 + 875 = 1148 \text{ K}$$

$$T_1 = 27 + 273 = 300 \text{ K}$$

$$c_p = 1.0 \text{ kJ/kg-K}, \gamma = 1.4$$

$$P_1 = 1 \text{ bar}, P_2 = 4 \text{ bar (Since pressure ratio is 4)}$$

$$C = 42,000 \text{ kJ/kg}$$

$$\eta_{CC} = 90 \%$$

(Since loss in combustion chamber is 10 %)

For isentropic compression 1-2,

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} = (4)^{\frac{1.4-1}{1.4}} = 1.486$$

$$T_2 = 300 \times 1.486 = 445.8 \text{ K}$$

$$\eta_C = \frac{T_2 - T_1}{T_2' - T_1}$$

$$0.8 = \frac{445.8 - 300}{T_2' - 300}$$

$$T_2' = 482.25 \text{ K}$$

Now,

Heat supplied by the fuel = Heat taken by the burning gases

$$0.9 \times m_f \times C = (\dot{m}_a + m_f) \times c_p (T_3 - T_2')$$

$$C = \left(\frac{m_a + m_f}{m_f} \right) \times \frac{c_p (T_3 - T_2')}{0.9}$$

$$42000 = \left(\frac{m_a + 1}{m_f} \right) \times \frac{1(1148 - 482.25)}{0.9}$$

$$42000 = 739.72 \left(\frac{m_a}{m_f} + 1 \right)$$

$$\frac{m_a}{m_f} = \frac{42000}{739.72} - 1 = 55.78 \approx 56$$

$$\therefore \text{Air / fuel ratio} = 56 : 1$$

5.25. Compute the air standard efficiency of a Brayton cycle operating between a pressure of 1 bar and a final pressure of 12 bar. Take $\gamma = 1.4$.

Ans.

$$\text{Given: } P_1 = 1 \text{ bar}, P_2 = 12 \text{ bar}, \gamma = 1.4$$

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

$$r_p = \frac{P_2}{P_1} = 12$$

$$\text{So, } \eta = 1 - \frac{1}{(12)^{\frac{1.4-1}{1.4}}} = 50.8 \%$$

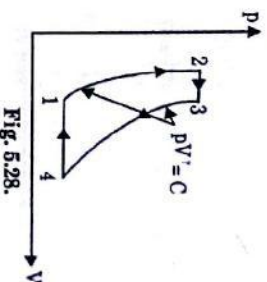


Fig. 5.28.

5.26. How do you classify gas turbines? Draw the p-V and T-s diagrams for a simple constant pressure open cycle gas turbine (No description is required).

In an open-cycle-constant-pressure gas turbine, air enters the compressor at a pressure of 1 bar and temperature of 25 °C, and is compressed up to a pressure of 4.2 bar. The isentropic efficiencies of compressor and turbine are 80 % and 85 % respectively. The peak cycle temperature is 1045 K. Assuming $\gamma = 1.4$, both for air and gases, and $c_p = 1.005 \text{ kJ/kg-K}$, determine:

(i) The power developed.

[UPTU 2002-03, Marks 10]

(ii) The thermal efficiency.

Ans. Gas turbine: Refer Q.5.4, and Q.5.5.

Given:

$$P_1 = 1 \text{ bar}, T_1 = 25 + 273 = 298 \text{ K}$$

$$P_2 = 4.2 \text{ bar}, T_3 = 1045 \text{ K}, \eta_c = 80 \%, \eta_T = 85 \%$$

$$\gamma \text{ for air and gases} = 1.4, c_p = 1.005 \text{ kJ/kg-K}$$

(i) Power developed:

$$\text{Work done} = \text{Turbine work} - \text{Compressor work}$$

$$= c_p (T_3 - T_4) - c_p (T_2 - T_1)$$

For process 1-2, $\frac{P_2}{P_1} = \frac{P_3}{P_4} = r_p = \frac{4.2}{1} = 4.2$

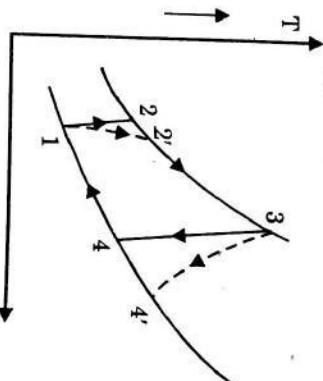


Fig. 5.29.

$$T_2 = T_1 \left(\frac{P_2}{P_1} \right)^{\frac{(\gamma-1)}{\gamma}}$$

$$T_2 = 298 (4.2)^{\frac{1.4-1}{1.4}}$$

$$T_2 = 449 \text{ K}$$

From compressor efficiency,

$$\eta_c = \frac{T_2 - T_1}{T_2' - T_1}$$

$$0.80 = \frac{449 - 298}{T_2' - 298}$$

$$T_2' = 486.75 \text{ K}$$

For process 3-4,

$$T_4 = T_3 \left(\frac{P_4}{P_3} \right)^{\frac{(\gamma-1)}{\gamma}}$$

$$T_4 = 1045 \left(\frac{1}{4.2} \right)^{\frac{1.4-1}{1.4}}$$

$$T_4 = 693.5 \text{ K}$$

From turbine efficiency,

$$\eta_r = \frac{T_3 - T_4}{T_3 - T_4'}$$

$$0.85 = \frac{1045 - T_4'}{1045 - 693.5}$$

$$T_4' = 746.23 \text{ K}$$

$$\begin{aligned} \text{Work done} &= 1.005 (1045 - 746.23) - 1.005 (486.75 - 298) \\ &= 110.57 \text{ kJ/kg} \end{aligned}$$

$$\begin{aligned} \text{Power developed} &= \text{Work done per second} \\ &= 110.57 \text{ kJ/kg-s} \end{aligned}$$

(ii) Thermal efficiency:

$$\begin{aligned} \text{Heat supplied} &= c_p (T_3 - T_2) \\ &= 1.005 (1045 - 486.75) \\ &= 561.04 \text{ kJ/kg} \end{aligned}$$

$$\begin{aligned} \text{Thermal efficiency} &= \frac{\text{Work done}}{\text{Heat supplied}} \\ &= \frac{110.57}{561.04} = 0.197 \text{ or } 0.20 = 20\% \end{aligned}$$

5.27.

An open cycle gas turbine draws air at 1 kgf/cm² and 15 °C and compresses it through a pressure ratio of 6. The compressed air is then fed to the combustion chamber to raise the temperature of the combustion products to 1000 °C. The working medium then expands to an intermediate pressure in the HP turbine which drives the compressor. Further expansion continues in the LP turbine. Find the specific output and overall thermal efficiency. Assume polytropic efficiency of compression = 85 %, isentropic efficiency for both the turbines = 90 %, maximum temperature = 900 K, thermal ratio = 0.75, for air $c_p = 0.24 \text{ kcal/kg-K}$, $\gamma = 1.4$ and for gases $c_p = 0.27 \text{ kcal/kg-K}$, $\gamma = 1.33$. [UPTU 2012-13, Marks 10]

Ans.

Given:

$$\text{Inlet pressure, } P_1 = 1 \text{ kgf/cm}^2 = 98100 \text{ N/m}^2$$

$$\text{Inlet temperature, } T_1 = 15^\circ \text{C} = 288 \text{ K}$$

$$\text{Pressure ratio} = 6 = \frac{P_2}{P_1}$$

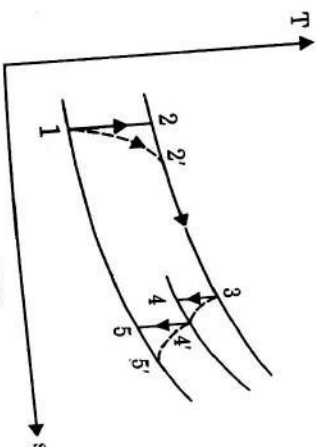


Fig. 5.30.

$$\text{Maximum temperature } (T_3) = 900 \text{ K}$$

$$\text{Efficiency of compressor } (\eta_c) = 85 \%$$

$$\text{Isentropic efficiency for both turbines } (\eta_r) = 90 \%$$

Thermal ratio = 0.75

Isentropic compression 1-2,

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = (6)^{\frac{0.4}{1.4}} = 1.67$$

$$T_1 = 288 \times 1.67$$

$$T_2 = 480.96 \text{ K}$$

$$\eta_c = \frac{T_2 - T_1}{T_2 - T_1}$$

$$0.85 = \frac{480.96 - 288}{T_2 - 288}$$

$$T_2 = 515.01 \text{ K}$$

Work output of H.P. turbine = Work input to compressor

$$c_{pg}(T_3 - T_4) = c_{pg}(T_2 - T_1)$$

$$0.27(900 - T_4) = 0.24(515.01 - 288)$$

$$T_4 = 698.213 \text{ K}$$

$$[\because 1 \text{ kcal/kg-K} = 4.18 \text{ kJ/kg-K}]$$

$$\text{For H.P. turbine, } \eta_r = 0.90 = \frac{T_3 - T_4}{T_3 - T_4} = \frac{900 - 698.213}{T_3 - T_4}$$

$$T_4 = 675.79 \text{ K}$$

For isentropic expansion, 3-4

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}}$$

$$\left(\frac{T_3}{T_4}\right)^{\frac{\gamma}{\gamma-1}} = \frac{P_3}{P_4}$$

$$\frac{P_3}{P_4} = \left(\frac{900}{675.79}\right)^{\frac{1.33}{0.33}} = 3.173$$

[For gases $\gamma = 1.33$ (given)]

$$P_4 = \frac{P_3}{3.173} = \frac{98100 \times 6}{3.173} = 185502.68 \text{ N/m}^2$$

For isentropic expansion, 4'-5

$$[P_3 = P_2 = 6 P_1]$$

$$\frac{T_4}{T_5} = \left(\frac{P_4}{P_5}\right)^{\frac{\gamma-1}{\gamma}}$$

$$\frac{T_4}{T_5} = \left(\frac{185502.68}{98100}\right)^{\frac{0.33}{1.33}} = 1.171$$

$$[\because P_1 = P_5 = 98100 \text{ N/m}^2]$$

$$T_5 = \frac{T_4}{1.171}$$

$$T_5 = \frac{698.213}{1.171}$$

$$T_5 = 596.25 \text{ K}$$

$$\eta_r = \frac{T_4 - T_5}{T_4 - T_5}$$

$$0.90 = \frac{698.213 - T_5}{698.213 - 596.25}$$

$$T_5 = 606.45 \text{ K}$$

$$\text{Net power output} = W_{\text{net(L.P.)}} = c_{pg}(T_4 - T_5)$$

$$= 0.27 \times 4.18 (698.213 - 606.45) = 103.56 \text{ kJ/kg}$$

$$\eta_{\text{thermal}} = \frac{\text{Net work output}}{\text{Heat supplied}}$$

$$= \frac{103.56}{c_{pg}(T_3 - T_2)} = \frac{103.56}{0.26 \times 4.18 (900 - 515.01)}$$

$$= 0.248$$

$$\eta_{\text{thermal}} = 24.8\%$$

528. State the merits and demerits of closed cycle gas turbine over open cycle gas turbine. What are the different methods by which performance of a gas turbine cycle can be improved? [UPTU 2004-05, Marks 10]

OR

Draw the flow and T-s diagrams of open and closed gas turbine cycle. Discuss the relative merit and demerits of closed cycle over open cycle. [UPTU 2008-09, Marks 10]

Ans. Merits of closed cycle gas turbine over open cycle gas turbine:

1. Closed cycle gas turbines are external combustion plants. So it uses a wide variety of cheap fuels like coal etc. and there is no direct contact of turbine blades with products of combustion which reduces fouling of blades.
2. Open cycle gas turbine must operate on air while closed cycle gas turbine may use any fluid which gives increased plant efficiency and power output.
3. Open cycle gas turbine plants have low part load efficiency because turbine inlet temperature controls the load regulation whereas closed cycle gas turbine operates at constant speed and load regulation can easily be controlled by changing the pressure level in the system by keeping temperature constant.

4. In closed cycle gas turbines, the minimum operating pressure is to be set above the atmospheric pressure. Due to increased inlet pressure, the specific volume for working fluid reduces which results in reduction of the size of heat exchangers and piping. Whereas in open cycle gas turbine working fluid (air) enters at atmospheric pressure which increases its size.

Demerits of closed cycle gas turbine over open cycle gas turbine:

1. Open cycle gas turbine has efficient internal combustion which is not present in closed cycle gas turbine.
2. Closed cycle gas turbine has complicated and costly system. It requires air-heaters which also increases its cost.
3. In open cycle gas turbine atmosphere acts as sink and it does not require any coolant for precooling of exhaust gases entering into compressor from turbine. But closed cycle gas turbine requires a precooling.

Performance improvement methods of turbine: Refer Q. 5.12. T - s diagram for open and closed cycle see Fig. 5.2 (a) and (b).

- 5.29. Consider a gas turbine working on Brayton cycle. The air enters the compressor at 0.15 MPa and 20 °C. The maximum pressure and temperature of the cycle are 1.2 MPa and 1200 °C respectively. Calculate the pressure and temperature at each point in the cycle and cycle efficiency and turbine work for following two cases:
- (i) Theoretical Brayton cycle, and
 - (ii) Actual Brayton cycle with turbine and compressor efficiencies of 0.85 each.

Ans. Given: $P_1 = 0.15 \text{ MPa}$, $P_2 = 1.2 \text{ MPa}$ [UPTU 2005-06, Marks 10]
 $T_1 = 20^\circ\text{C} = 20 + 273 = 293 \text{ K}$
 $T_3 = 1200^\circ\text{C} = 1200 + 273 = 1473 \text{ K}$

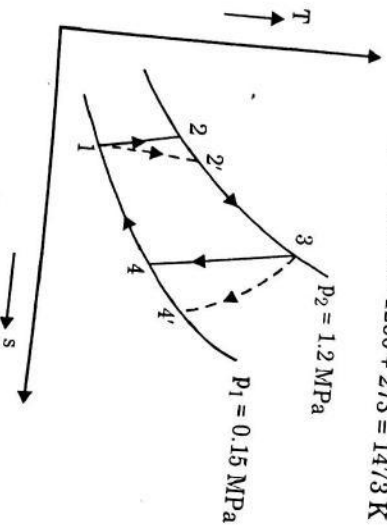


Fig. 5.31.

(i) For theoretical Brayton cycle:

$$r_p = \frac{P_2}{P_1} = \frac{1.2}{0.15} = 8$$

$$\text{For process 1-2, } \frac{T_2}{T_1} = (r_p)^{\frac{\gamma-1}{\gamma}}$$

$$\gamma \text{ for air} = 1.4, T_2 = 293 \times 8^{1/5} = 530.75 \text{ K}$$

$$\text{For process 3-4, } \frac{T_4}{T_3} = \frac{1}{(r_p)^{\frac{\gamma-1}{\gamma}}}$$

$$T_4 = \frac{1473}{(8)^{1/5}} = 813.16 \text{ K}$$

$$\text{Turbine work} = c_p (T_3 - T_4)$$

$$= 1.005 (1473 - 813.16) \text{ kJ/kg} = 663.14 \text{ kJ/kg}$$

$$\text{Cycle efficiency} = \frac{\text{Net work done}}{\text{Heat supplied}}$$

$$= \frac{c_p (T_3 - T_4) - c_p (T_2 - T_1)}{c_p (T_3 - T_2)} = \frac{(1473 - 813.16) - (530.75 - 293)}{(1473 - 530.75)} = 0.448$$

$$\text{Cycle efficiency} = 0.448 \text{ or } 45\%$$

$$\text{So, } (P_1, T_1) = (0.15 \text{ MPa}, 293 \text{ K}),$$

$$(P_2, T_2) = (1.2 \text{ MPa}, 530.75 \text{ K}),$$

$$(P_3, T_3) = (1.2 \text{ MPa}, 1473 \text{ K}), \text{ and}$$

$$(P_4, T_4) = (0.15 \text{ MPa}, 813.16 \text{ K}).$$

(ii) For actual Brayton cycle:

With compressor efficiency = 0.85 = Turbine efficiency

$$\text{So, } \eta_c = \frac{T_2 - T_1}{T_2' - T_1}$$

$$0.85 = \frac{530.75 - 293}{T_2' - 293}$$

$$T_2' = 572.7 \text{ K}$$

and

$$\eta_t = \frac{T_3 - T_4'}{T_3 - T_4}$$

$$0.85 = \frac{1473 - T_4'}{1473 - 813.16}$$

$$T_4' = 912.14 \text{ K}$$

$$\text{Cycle efficiency} = \frac{\text{Net work done}}{\text{Heat supplied}}$$

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

$$= \frac{(1473 - 912.14) - (572.7 - 293)}{(1473 - 572.7)}$$

$$= 0.31 \text{ or } 31\%$$

$$\text{Turbine work} = c_p(T_3 - T_4) = 1.005(1473 - 912.14)$$

$$= 563.66 \text{ kJ/kg}$$

5.30. Prove that optimum pressure ratio for maximum specific output for a gas turbine plant is given by

$$r_p = \left[\eta_{\text{turbine}} \times \eta_{\text{compressor}} \times \frac{T_3}{T_1} \right]^{\frac{\gamma}{2(\gamma-1)}}$$

[UPTU 2006-07, 2007-08; Marks 10]

Ans. Let us consider a gas turbine having initial and maximum cycle temperature T_1 and T_3 respectively. The compressor and turbine used in the gas turbine have their efficiencies $\eta_{\text{compressor}}$ and η_{turbine} respectively.

$$\text{Work output} = \text{Turbine work} - \text{Compressor work}$$

$$= C_p(T_3 - T_4) - C_p(T_2 - T_1)$$

$$\text{Heat supplied} = C_p(T_3 - T_2)$$

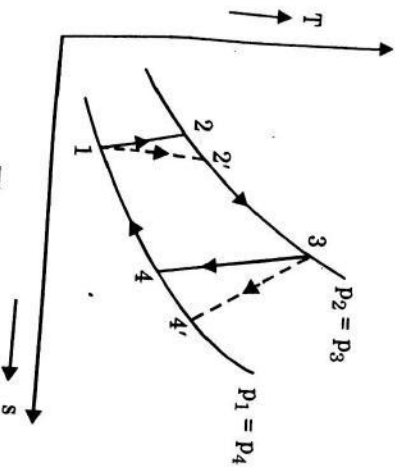


Fig. 5.32.

From compressor efficiency,

$$\eta_c = \frac{T_2 - T_1}{T_2' - T_1}$$

$$\Rightarrow T_2 - T_1 = \frac{(T_2' - T_1)}{\eta_c}$$

From turbine efficiency,

$$\eta_t = \frac{T_3 - T_4}{T_3 - T_4'}$$

$$T_3 - T_4 = \eta_t(T_3 - T_4')$$

$$\text{Work output} = C_p \eta_t (T_3 - T_4) - C_p (T_2 - T_1)$$

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

$$\text{Now we have } \frac{T_3}{T_1} = \left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} = \frac{T_2}{T_1}$$

$$\text{where, } r_p = \frac{P_2}{P_1} \text{ and } z = \frac{\gamma-1}{\gamma} \text{ (Let)}$$

$$\text{So, } W = C_p \eta_t T_3 \left(1 - \frac{1}{r_p^z} \right) - C_p \frac{T_2}{T_1} (r_p^z - 1)$$

For maximum specific output,

$$\frac{dW}{dr_p} = 0$$

$$C_p \eta_t T_3 \left(0 + \frac{z}{r_p^{z+1}} \right) - C_p \frac{T_2}{T_1} (z r_p^{z-1}) = 0$$

$$\eta_t \cdot \frac{T_3}{r_p^{z+1}} = \frac{T_2}{T_1} r_p^{z-1}$$

$$r_p^{2z} = \eta_t \cdot \eta_c \cdot \frac{T_3}{T_1}$$

$$r_p = \left(\eta_t \cdot \eta_c \cdot \frac{T_3}{T_1} \right)^{\frac{1}{2z}}$$

$$\text{Put, } z = \frac{\gamma-1}{\gamma}$$

$$r_p = \left(\eta_t \cdot \eta_c \cdot \frac{T_3}{T_1} \right)^{\frac{\gamma}{2(\gamma-1)}}$$

$$r_p = \left[\eta_{\text{turbine}} \times \eta_{\text{compressor}} \times \frac{T_3}{T_1} \right]^{\frac{\gamma}{2(\gamma-1)}}$$

CONCEPT OUTLINE 3

Jet propulsion : Principle of jet propulsion involves imparting momentum to a mass of fluid in such a manner that the reaction of imparted momentum provides a propulsive force.

Classification : Propulsion system may be classified as follows :

1. Air stream jet engines (Air breathing engines)
2. Self contained rocket engines (Non air breathing engines)

Performance of jet propulsion engines : Thrust obtained per kg air (N/kg of air/s),

$$T = \left[\left(1 + \frac{m_f}{m_a} \right) C_e - C_a \right] + \frac{A_e}{m_a} (p_e - p_a)$$

Thrust power :

$$TP = T \times C_a$$

Propulsion power :

$$PP = KE_{\text{leaving}} - KE_{\text{entering}} = \Delta KE = \frac{1}{2} \left(1 + \frac{m_f}{m_a} \right) C_e^2 - \frac{C_a^2}{2}$$

Propulsive efficiency :

$$\eta_{\text{prop}} = \frac{TP}{PP} = \frac{\left[\left(1 + \frac{m_f}{m_a} \right) C_e - C_a \right] C_a}{\frac{1}{2} \left[\left(1 + \frac{m_f}{m_a} \right) C_e^2 - C_a^2 \right]}$$

Thermal efficiency :

$$\eta_{\text{th}} = \frac{\text{Kinetic energy available}}{\text{Heat supplied}} = \frac{\left(1 + \frac{m_f}{m_a} \right) C_e^2 - C_a^2}{2 \left(\frac{m_f}{m_a} \right) \times \text{Calorific value of fuel}}$$

Overall efficiency :

$$\eta_o = \frac{\left(1 + \frac{m_f}{m_a} \right) C_e - C_a}{\left(1 + \frac{m_f}{m_a} \right) \times \text{Calorific value of fuel}}$$

$$\eta_o = \eta_{\text{th}} \times \eta_{\text{prop}}$$

Jet efficiency : It is the ratio of final kinetic energy in jet to the total of isentropic heat drop in jet pipe and carry over from turbine.

Rocket propulsion : It is realised by the thrust produced by combustion products leaving exit nozzle.

Rocket engines : Rocket engines are non-air breathing engines and carry their own oxidiser for burning of fuel.

5.31. Explain the principle of a jet propulsion system. Where is it used ?

Ans.

Principle of jet propulsion system : Jet propulsion refers to the imparting of forward motion to the object as a reaction to exit of high velocity gas or liquid stream from the rear end of object. It is based on the principle of Newton's second law and third law of motion. Due to change of momentum in fluid stream, the reaction to the impulse is created which gives propelling thrust for the engine. Thus, the change of momentum of the fluid stream flowing across engine and the reaction to the impulse due to change in momentum is responsible for jet propulsion.

When high temperature and pressure gas stream is expanded through a nozzle, comes out in atmosphere with significantly high velocity, and gives a change of momentum which produces impulse force and its reaction produces propelling thrust.



Fig. 5.33. Principle of jet propulsion system.

Consider, p_a = atmospheric pressure, A_i and A_e = cross-sectional area at inlet and exit, p_i and p_e = pressure at inlet and exit, and C_i and C_e = velocity of gas at inlet and exit.

Let m_a , mass of air entering into engine per second and mass rate of fuel is m_f and it is constant.

Case 1 : If mass of fuel added is negligible.

Momentum thrust = $T_m = m_a (C_e - C_i)$

Case 2 : If mass of fuel added is to be considered.

$$\begin{aligned} \text{Momentum thrust} &= m_a (C_e - C_i) + m_f C_e \\ &= (m_a + m_f) C_e - m_a C_i \end{aligned}$$

Case 3 : If the expansion is incomplete then two types of thrust will develop.

(a) Momentum thrust (T_m)

(b) Pressure thrust (T_p)

$$\text{Total thrust } (T) = T_m + T_p = m_a (C_e - C_i) + A_e (p_e - p_i)$$

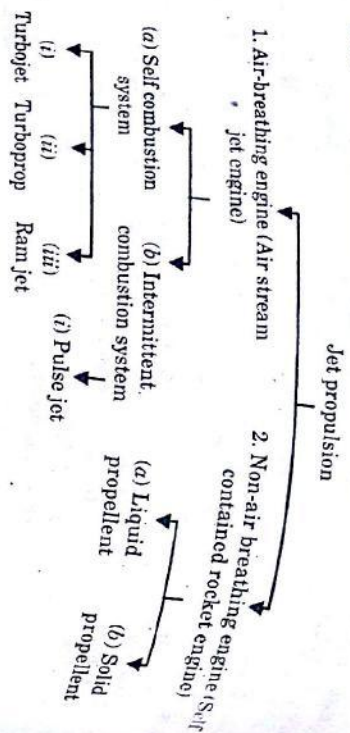
Consider mass of fuel added then,

$$T = [(m_a + m_f) C_e - m_a C_i] + A_e (p_e - p_i)$$

Uses : It is used in high speed, high altitude aircrafts, missiles and space crafts etc.

5.32. Give the classification of jet propulsion.

Ans. Classification of jet propulsion :



5.33. What are the performance differences between air breathing engine and the rocket engines ?

OR

What are the major differences between air breathing engines and rocket engines ? Explain.

Ans.

Air-breathing engine	Rocket engine
1. There is an altitude limitation. 2. Thrust decreases with altitude. 3. Rate of climb decreases with altitude. 4. Engine ram drag increases with flight speed. 5. Flight speed always less than jet velocity. 6. It has compared less efficiency and reasonable flight duration.	1. There is no altitude limitation. It can travel in space. 2. Thrust increases slightly with altitude. 3. Rate of climb increases with altitude. 4. Engine has no ram drag, so there is a constant thrust with speed. 5. Flight speed can be greater than jet velocity. 6. It has low efficiency at extremely high flight speed for small duration.

5.34. Explain construction and working of turbojet engine with neat sketch and diagram.

Ans. Construction : A turbojet engine consists of a diffuser at the entrance before the compressor (axial flow type rotary compressor) and a nozzle at exit after the turbine.

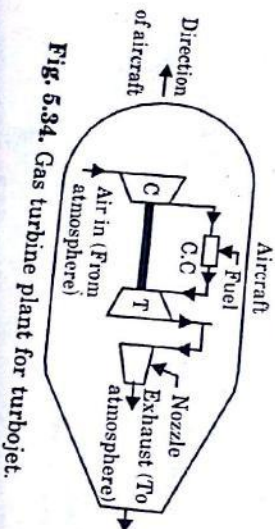


Fig. 5.34. Gas turbine plant for turbojet.

Gas Turbine and Jet Propulsion

229 (ME-4) B

At entrance, diffuser slows down the air (because velocity of air entering is equal to the plane speed) and its kinetic energy is converted into pressure and this compression is known as ram compression. This compressed air is again compressed into compressor up to a pressure of 3 to 4 bar. This compressed air enters the combustion chamber where fuel is added and combustion occurs at constant pressure that results in rise of temperature rapidly. These hot gases from combustion chamber are expanded partially into turbine and developing the power from turbine. This power is just sufficient to drive the compressor, fuel pump and other auxiliaries.

The exhaust gases from turbine are at higher pressure than the atmospheric pressure. These gases are expanded in a nozzle and very high velocity jet is produced which provides a forward motion to the aircraft by the jet reaction according to Newton's third law of motion.

The turbojets are more suited to the aircrafts travelling above 800 km/h. It gives higher propulsion efficiency at higher speeds.

Overall efficiency of turbojet = $\eta_{\text{thermal}} \times \eta_{\text{propulsive}}$

T-s diagram :

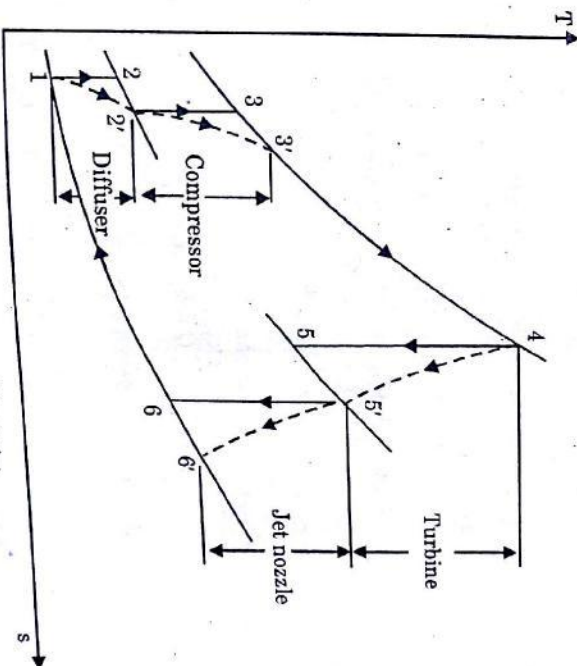


Fig. 5.32. T-s diagram of turbojet.

Process 1-2 : It shows ram compression with 100 % efficient diffuser. In ideal diffuser velocity of air at point 2 is equal to zero ($C_2 = 0$). Process 1-2' is real process.

Process 2-3 : Isentropic compression of air and 2'-3' shows actual compression of air.

Process 3-4: Ideal addition of heat at constant pressure $p_3 = p_4$. Process 3'-4 shows actual addition of heat.

Process 4-5: Isentropic expansion of gas in turbine. Process 4-5 is actual expansion in turbine.

Process 5-6: Isentropic expansion of gas in nozzle. Process 4-5 is actual expansion of gas in nozzle.

Expressions: Let 1 kg of working fluid is flowing through the system.

1. **Diffuser:** For process 1-2, the energy equation is

$$\frac{C_1^2}{2} + h_1 + Q_{1-2} = \frac{C_2^2}{2} + h_2 + W_{1-2}$$

For ideal diffuser, $C_2 = 0$, $Q_{1-2} = 0$, $W_{1-2} = 0$

$$\text{So, } h_2 = h_1 + \frac{C_1^2}{2}$$

$$\text{or } T_2 = T_1 + \frac{C_1^2}{2C_p}$$

For diffuser efficiency,

$$\eta_d = \frac{h_2 - h_1}{h_2 - h_1} = \frac{T_2 - T_1}{T_2' - T_1}$$

$$h_2 = h_1 + \frac{C_1^2}{2\eta_d}$$

$$\text{or } T_2 = T_1 + \frac{C_1^2}{2C_p \cdot \eta_d}$$

2. **Compressor:** Ideal work expanded in compressor

$$W_c = h_3 - h_2 = C_p (T_3 - T_2)$$

$$\text{Actual work} = h_3 - h_2 = \frac{h_3 - h_2}{\eta_c}$$

3. **Combustion chamber:**

Ideal heat supplied per kg,

$$Q = h_4 - h_3 = C_p (T_4 - T_3)$$

$$\text{Actual heat supplied} = \left(1 + \frac{m_f}{m_a}\right) h_4 - h_3$$

$$\text{or } = C_{p_{\text{mix}}} \left(1 + \frac{m_f}{m_a}\right) T_4 - C_{p_{\text{air}}} \cdot T_3$$

4. **Turbine:**

$$\text{Turbine work, } W_t = h_4 - h_5$$

$$= C_p (T_4 - T_5)$$

$$\text{Actual turbine work} = h_4 - h_5 = C_p (T_4 - T_5)$$

$$= C_p (T_4 - T_5) \times \eta_t$$

$$\text{For simplification, turbine work} = \text{compressor work}$$

5. **Jet nozzle:** For process 5-6,

$$h_6 + \frac{C_6^2}{2} = h_5 + \frac{C_5^2}{2}$$

For actual process,

$$h_6 + \frac{C_6^2}{2} = h_5 + \frac{C_5^2}{2}$$

Thermal efficiency η_{th} is given by

$$\eta_{th} = \frac{(h_4 - h_6) - (h_3 - h_1)}{(h_4 - h_5) - (h_3 - T_1)} = \frac{(T_4 - T_6) - (T_3 - T_1)}{(T_4 - T_5) - (T_3 - T_1)}$$

5.35. Explain the following terms related to performance of jet propulsion engines: (i) Thrust power (ii) Propulsive power

(iii) Propulsive efficiency (iv) Thermal efficiency (v) Overall efficiency (vi) Jet efficiency.

OR

Write short note on propulsive power and propulsive efficiency. [UPTU 2010-11, Marks 05]

OR

Define propulsive power and propulsive efficiency and also give their mathematical expression. [UPTU 2012-13, Marks 05]

Ans. (i) **Thrust power (T.P.):** Let us consider the turbojet engine moving with velocity C_a through air. Thus the velocity of air entering engine would be C_a (approach velocity), if the atmospheric air is at rest. Thrust obtained per kg of air,

$$T = \left[\left(1 + \frac{m_f}{m_a}\right) C_e - C_a \right] + \frac{A_e}{m_a} (p_e - p_a)$$

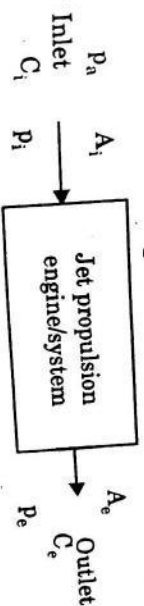


Fig. 5.36. Principle of jet propulsion system.

It refers to the work done per unit time by the engine and is given by the product of thrust and velocity with which engine moves (flight velocity).

$$T.P. = T \times C_a = \left[\left(1 + \frac{m_f}{m_a}\right) C_e - C_a \right] + \frac{A_e}{m_a} (p_e - p_a) \times C_a$$

Neglecting the pressure thrust,

$$T.P. = \left[\left(1 + \frac{m_f}{m_a} \right) C_e - C_a \right] \cdot C_a$$

Neglecting the mass of fuel added,

$$T.P. = (C_e - C_a) \cdot C_a \text{ W/kg of air}$$

(ii) **Propulsive power ($P.P.$)**: It is defined as the difference between the rate of kinetic energy entering with air and leaving with jet of exit gases.

$$P.P. = K.E._{\text{leaving}} - K.E._{\text{entering}} = \Delta K.E.$$

$$= \frac{1}{2} \left(1 + \frac{m_f}{m_a} \right) C_e^2 - \frac{C_a^2}{2} \text{ W/kg of air}$$

Neglecting fuel mass addition, propulsive power,

$$P.P. = \frac{C_e^2 - C_a^2}{2} \text{ W/kg of air}$$

(iii) **Propulsive efficiency (η_{prop})**: It is defined as the ratio of thrust power to propulsive power. It is also called Froude efficiency.

$$\eta_{\text{prop}} = \frac{\text{Thrust power}}{\text{Propulsive power}} = \frac{\left[\left(1 + \frac{m_f}{m_a} \right) C_e - C_a \right] \cdot C_a}{\frac{1}{2} \left[\left(1 + \frac{m_f}{m_a} \right) C_e^2 - C_a^2 \right]}$$

If fuel mass is neglected then,

$$\eta_{\text{prop}} = \frac{2(C_e - C_a) \cdot C_a}{(C_e^2 - C_a^2)}$$

$$= \frac{2}{1 + \left(\frac{C_e}{C_a} \right)}$$

It tells how much propulsive power is transformed into thrust power.

Note: If $C_e = C_a$ then

$$\eta_{\text{prop}} = 1$$

(iv) **Thermal efficiency (η_{th})**: It is defined as the ratio of total kinetic energy available and total heat supplied.

$$\eta_{\text{th}} = \frac{\text{Kinetic energy available}}{\text{Heat supplied}} = \frac{\left\{ \frac{1}{2} (m_a + m_f) C_e^2 - m_a C_a^2 \right\}}{m_f \times C.V.}$$

$$= \frac{\left[\left(1 + \frac{m_f}{m_a} \right) C_e^2 - C_a^2 \right]}{2 \left(\frac{m_f}{m_a} \right) \times C.V.}$$

where, $\frac{m_f}{m_a}$ = Fuel-air ratio and
C.V. = Calorific value of fuel.

(v) **Overall efficiency (η_{overall})**: It is defined as the ratio of useful work done to the energy supplied.

$$\eta_{\text{overall}} = \frac{\left[\left(1 + \frac{m_f}{m_a} \right) \cdot C_e - C_a \right] C_a}{\left(\frac{m_f}{m_a} \right) \times C.V.}$$

Note: For maximum overall efficiency,

$$C_e = \frac{1}{2} C_a$$

(vi) **Jet efficiency (η_{jet})**: It is defined as the ratio of final kinetic energy in jet to the total of isentropic heat drop in jet pipe and carry over from turbine.

$$\eta_{\text{jet}} = \frac{\text{Final kinetic energy in jet}}{\text{Isentropic heat drop in the jet pipe} + \text{Carry over from the turbine}}$$

5.36. Give the advantages and disadvantages of turbojet engines.

Ans. Advantages of turbojet engine:

1. Turbojet engine is simple in construction.
2. Vibrations are absent in turbojet engine.
3. More than 3000 km/h speed can be achieved easily.
4. As compared to reciprocating type aero-engine weight to power ratio is superior.
5. Power supply is uninterrupted and smooth.
6. Large range of mixture strength fuel can be burnt.
7. Maximum altitude ceiling can be achieved as compared to turboprop and conventional piston type engines.

Disadvantages:

1. Life of unit is comparatively shorter.
2. Below 550 km/h turbojet becomes rapidly inefficient.
3. It produces more noise.
4. It requires a longer strip to take off.
5. It requires expensive materials.

5.37. Explain with neat sketch and diagrams the principle of turboprop. Also explain what is Ram effect?

OR

Short note turbojet and turboprop engines

OR

[UPTU 2010-11, Marks 05]

With the help of neat sketch explain the working of turboprop engine.

Ans.

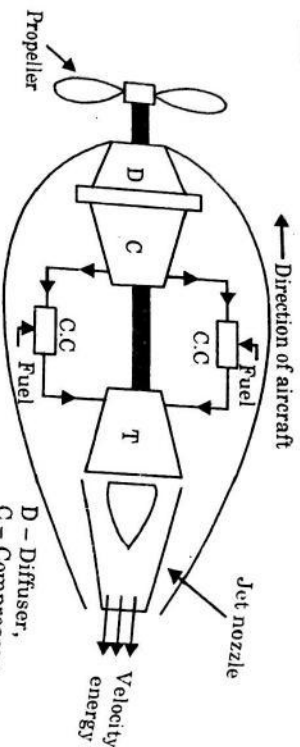


Fig. 5.37. Turboprop.

Construction: Turboprop engine, also called turbo shaft engine or prop-jet engine.

It consists of following parts such as:

- (a) **Compressor:** To compress the inlet air.
- (b) **Combustion chamber:** To burn the compressed air with fuel.
- (c) **Turbine:** To expand the burnt air-fuel mixture.
- (d) **Nozzle:** Expansion of burnt air-fuel mixture occur which propel the turboprop engine.

Principle and working: About 80 % expansion of gases take place in turbine and 20 % expansion takes place in nozzle. The turbine develops power to run the compressor and propeller. The propeller and jet produced by the nozzle give forward motion to the air craft.

By using diffuser before the compressor, overall efficiency of the turboprop is improved.

Ram effect: It is the phenomenon of compression that occurs in kinetic energy of the incoming air (equal to aircraft velocity) into pressure energy. This type of compression is known as Ram effect.

Advantages: This system is employed in aircrafts. It has low take-off and high propulsive efficiency at speeds below 600 km/h.

5.38. What are the differences between turbojet engine and turboprop engine?

OR

Make comparison between turbojet and turboprop engines.

[UPTU 2012-13, Marks 05]

Ans.

Turboprop is a turbine powered propeller that works in the same aspect. It produces a lot of thrust to climb to higher altitudes than normal aspirated engine or turbo charged engines. Turbojet is a fully contained jet propulsion system that compresses all of its air some with 20 % bypass and ignites it before exiting the turbine. Turboprop has a greatly larger sized mass due to carry a lot of cargo which causes it to have lower acceleration, whereas the turbojet has a small amount of mass causing it to have a higher amount of acceleration.

5.39. Explain with sketch and diagrams the construction, working, advantages and limitations of Ram jet.

OR

Discuss the working of turboprop and Ram jet engines

[UPTU 2009-10, Marks 05]

Ans.

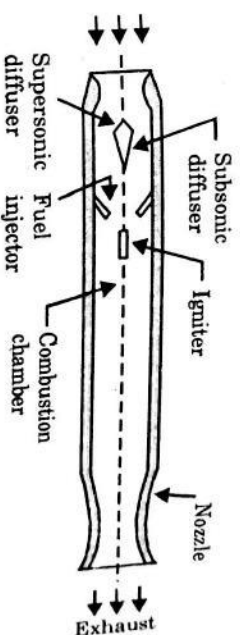


Fig. 5.38. Schematic diagram of a Ram jet propulsion unit.

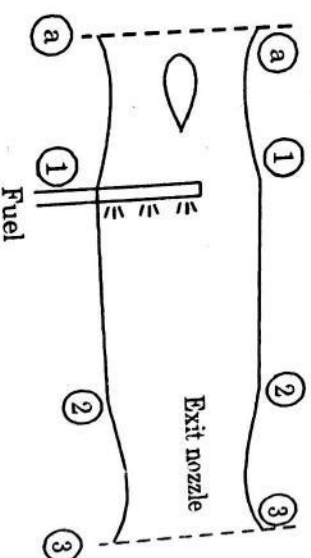


Fig. 5.39. Schematic of Ram jet.

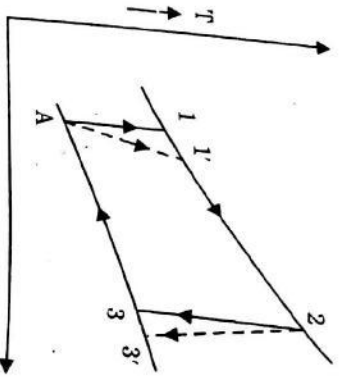


Fig. 5.40. T-s representation of Ram jet.

Construction and working : Ram jet is also called athodyd, Laminar tube or flying stove pipe. It consists of a diffuser, combustion chamber and nozzle. Diffuser has two portions: supersonic diffuser and subsonic diffuser. The air at supersonic speed enters the ram jet plant and is slowed down to sonic velocity in supersonic diffuser resulting into sudden rise of pressure which provides the formation of shock wave. Pressure is again increased in subsonic diffuser and temperature of air increases up to the ignition temperature. When this air enters the combustion chamber, fuel is injected by fuel injector and by means of a spark plug mixture is ignited. The expansion of gases towards the diffuser entrance is restricted by pressure barrier. So the hot gases are constrained to move towards the nozzle and undergo expansion and the pressure energy is converted into the kinetic energy. The high velocity gases leaving the nozzle provide forward thrust to the unit. At 1700 km/h to 2000 km/h flight speed, the performance of ram jet engine is best.

Advantages :

- (i) Ram jet is very simple in construction.
- (ii) It is light in weight.
- (iii) It requires no moving parts.
- (iv) A wide variety of fuels may be used.

Disadvantages :

- (i) It requires a small turbojet to start the ram jet.
- (ii) At low and moderate speeds, fuel consumption is too high.
- (iii) For successful operation, the diffuser needs to be designed carefully so that kinetic energy is efficiently converted into pressure energy.

5.40. Draw the schematic diagram of pulse-jet engine and also gives its construction and working details.

Ans. Pulse-jet engine :

Construction : The construction of pulse-jet engine is simple and shown in the Fig. 5.41.

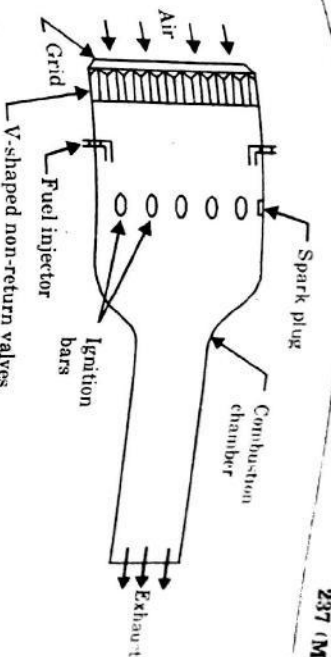


Fig. 5.41. Pulse-jet engine.

Working principle : Its development is due to the inability of the ram jet to be self starting. The air enters into diffuser section is compressed by ram effect in the diffuser section and the grid passages which are opened and closed by V-shaped non-return valves. By fuel injectors fuel is added into combustion chamber and combustion is initiated by a spark plug. The temperature and pressure of combustion products increases. As the combustion pressure becomes higher than the ram pressure, the non-return valves get closed and consequently the hot gases flow out of the tail pipe with high velocity and this will result in forward thrust. With the escape of gases to the atmosphere, the static pressure in the chamber falls and the high pressure air in the diffuser force the valves to open and fresh air is admitted inside the chamber for combustion during a new cycle.

Advantages :

- (i) It is cheap as compared to turbojet engine and produces static thrust.
- (ii) Pulse-jet engine produces thrust more than drag at lower speed compared to ram jet.

Disadvantages and limitations : It produces large noise and requires costly maintenance due to presence of valves. The vibrations and fuel consumption rate are high.

5.41. What is the principle used in rocket propulsion ?

OR

Explain the principle of rocket propulsion.

[UPTU 2009-10, Marks 05]

Ans. Principle of rocket propulsion : Rocket engines carry their own oxidizer for burning of fuel as they are non-air breathing engine. A simple layout of rocket engine is shown Fig. 5.42.

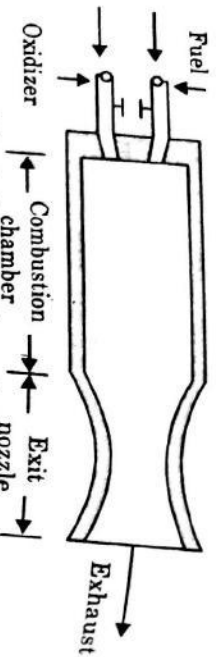
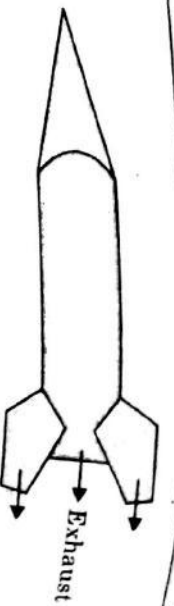


Fig. 5.42. Layout for rocket engine.

By combustion products leaving exit nozzle a thrust is produced for rocket propulsion. Thrust is available due to change of momentum and pressure with which jet comes out.

Consider, $\dot{m}_p$ = mass flow rate of propellant,
 C_e = jet exit velocity,
 A_e = area of exit nozzle,
 p_e = exit jet pressure, and
 p_a = atmospheric pressure.

So, net thrust available,

$$T = \dot{m}_p C_e + A_e (p_e - p_a)$$

For maximum thrust, exit jet velocity and pressure difference at exit should be maximized. The maximum thrust is available only when atmospheric pressure is zero ($p_a = 0$).

On comparing, we get
 $T = \dot{m}_p C_e + A_e (p_e - p_a) = \dot{m}_p \cdot C_e$

$$C_e = C_e + \frac{A_e}{\dot{m}_p} (p_e - p_a)$$

Specific impulse (I_{sp}): It is the thrust produced per unit mass flow rate of propellant.

$$I_{sp} = \frac{T}{\dot{m}_p} = C_e$$

Thrust power: $T.P. = T \cdot C_e = \dot{m}_p \cdot C_e \cdot C_e$
 Where, C_e = velocity with which rocket moves forward.
Propulsive efficiency:

$$\eta_{prop} = \frac{T.P.}{T.P. + \text{loss of kinetic energy}}$$

$$\eta_{prop} = \frac{\dot{m}_p \cdot C_e \cdot C_e}{\dot{m}_p \cdot C_e \cdot C_e + \frac{1}{2} \dot{m}_p (C_e - C_a)^2}$$

$$\eta_{prop} = \frac{2 \left(\frac{C_a}{C_e} \right)}{1 + \left(\frac{C_a}{C_e} \right)^2}$$

5.42. Explain the construction of rocket engines. What are the classifications of rocket engines? What are the desired properties of rocket propellant and applications?

OR

Discuss the basic theory and operation of a rocket engine.
 [UPTU 2011-12, Marks 05]

Ans.

Rocket engine:

Here,

FT = fuel tank,

HT = hydrogen peroxides tank,

O = oxidiser tank,

ST = steam turbine,

P_1, P_2 = pumps,

C.C. = combustion chamber,

H.G. = hot gases, and

N = nozzle.

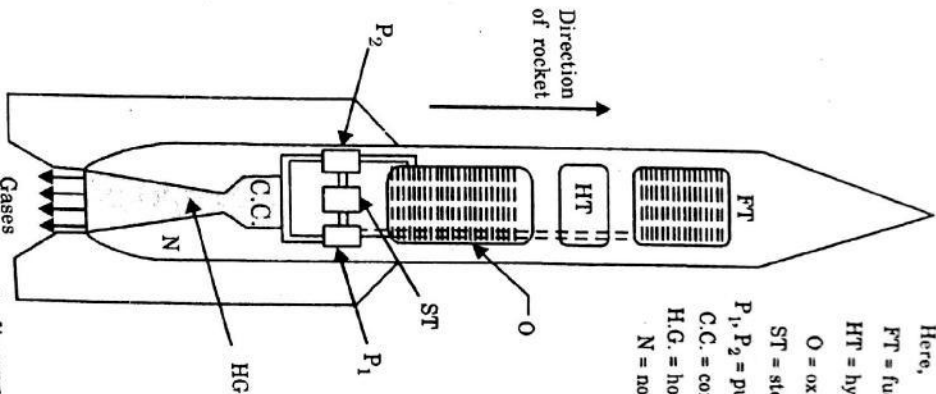


Fig. 5.43. Schematic diagram of a rocket.

Rocket engine consists of a fuel tank FT, an oxidizer tank O, two pumps P_1 and P_2 , a steam turbine ST and a combustion chamber C.C. Alcohol is filled in fuel tank and oxidizer tank is filled with liquid oxygen. The fuel and the oxidizer are supplied by the pumps to the combustion chamber where the fuel is ignited by electrical means. The pumps are driven with the help of steam turbine. The mixture of concentrated hydrogen peroxide with potassium permanganate produces the steam. Products of combustion are discharged from the combustion chamber through the nozzle N. So the rocket moves in opposite direction.

Classification of rocket engines :

1. According to type of propellants :

(i) Solid propellant rocket, and

(ii) Liquid propellant rocket.

2. According to the number of motors :

(i) Single-stage rocket, and

(ii) Multi-stage rocket.

Desired properties of propellant :

1. It should have large heating value.
2. It should have high density so that storage space required is small.
3. It should have stability and ease of handling and storage.
4. It should be non-toxic and non-corrosive.

Applications : It is used in serving air communication, satellite launching, spacecrafts, missiles, jet assisted air planes, pilot-less air craft etc.

5.43. Differentiate between jet propulsion and rocket propulsion.

Ans.

The main difference between jet propulsion and rocket propulsion is that in case of jet propulsion the oxygen required for combustion is taken from the atmosphere and fuel is stored whereas for rocket engine the fuel and oxidiser both are contained in a propelling body and as such it can function in vacuum.

