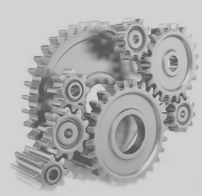
MECHANICAL ENGINEERING

Power Plant Engineering



Comprehensive Theory
with Solved Examples *and* Practice Questions

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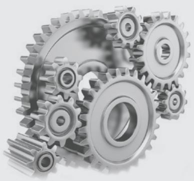

EDITIONS

First Edition : 2015
Second Edition : 2016
Third Edition : 2017
Fourth Edition : 2018
Fifth Edition : 2019
Sixth Edition : 2020
Seventh Edition : 2021
Eighth Edition : 2022
Ninth Edition : 2023

Tenth Edition : 2024

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CHAPTER

2

Fuels and Combustion

2.1 INTRODUCTION

The various types of fuels like liquied, solid and gaseous fuels are available for firing in boilers, furnaces and other combustion equipment. The selection of right type of fuel depends on various factors such as availability, storage, handling, pollution and landed cost of fuel.

The primary fuels which are burned to release heat and generate steam in boilers are the fossil fuels in the form of coal, fuel oil and natural gas, which represent the remains of plant and animal life that are preserved in the sedimentary rocks. Besides these, industrial wastes like blast furnace gas, coke oven gas, refinery gas, sugar factory refuse (bagasse), saw mill wood dust, rice husk, etc. are also used as boiler fuels, often to boost one of the primary fossil fuels. Coal is the principal energy source particularly in India because of its large deposits and availability.

When more than one type of fuel is simultaneously burned to meet the total heating requirement, the boiler is said to have a combination firing.

2.2 COAL

Coal is highly carbonaceous matter that has been formed as a result of alteration of vegetable matter (e.g., plants) under certain favourable conditions.

According to geological order of formation, coal may be of the following types.

- Peat — Not regarded as a rank of coal.
- Lignite — **Low rank**
- Sub-bituminous
- Bituminous
- Sub-anthracite
- Anthracite — **High rank**, less volatile, difficult to burn, higher heating value.

These are in the increasing percentage of carbon, they contains following characteristics:

- **Anthracite contains** more than **86% fixed carbon** and less volatile matter, **volatile matter helps in the ignition of coal.** So, it is often difficult to burn anthracite.

- **Bituminous** coal is the largest group containing **46–86% of fixed carbon** and **20–40% of volatile matter**. It can be **low volatile**, **medium volatile** and **high volatile**. Lower the volatility, higher the heating value and less it will smoke.
- **Lignite** is the lowest grade of coal containing moisture as high as 30% and high volatile matter.
- **Peat contains** up to 90% moisture and is not attractive as a utility fuel. It is a brown fibrous mass.

2.3 COAL ANALYSIS

There are two types of coal analysis.

(i) Proximate analysis (ii) Ultimate analysis

2.3.1 Proximate Analysis

- The proximate analysis indicates the percentage by weight of the fixed carbon, volatiles, ash and moisture content in coal. When 1 g sample of coal is subjected to a temperature of about 105ºC for a period of 1 hour, the loss in weight of the sample gives the moisture content of the coal.
- When 1 g sample of coal is placed in a covered platinum crucible and heated to 950ºC and maintained at that temperature for about 7 min, there is a loss in weight due to the elimination of moisture and volatile matter. Volatile matter consists of hydrogen and certain hydrogen-carbon compounds which can be removed from the coal simply by heating it.
- By subjecting 1 g sample of coal in an uncovered crucible to a temperature of about 720ºC until the coal is completely burned, a constant weight is reached, which indicates that there is only ash remaining in the crucible.
- Fixed carbon is the difference between 100% and the sum of the percentages of moisture, ash and volatile matter. It is also possible that some of this fixed carbon may include sulphur, nitrogen and oxygen.

  So, **Fixed carbon + Volatile matter + Moisture + Ash = 100%**

  $\Rightarrow$ ***FC* + *VM* + *M* + *A* = 100%** by mass.

- Lower rank coals (lower fuel ratio) are characterized by a greater oxygen content, that aids ignition and enhances combustibility and flame stability.
- High combustibility improves carbon burnout (reduces carbon carryover) and hence boiler efficiency and for pulverized coal-fired units, this allows the coal to be grinded to a coarser size.

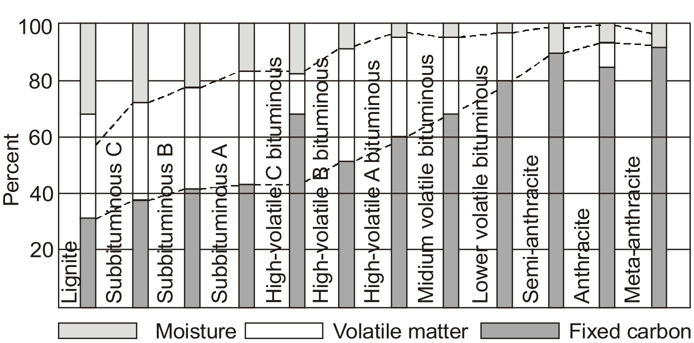

Figure: Fixed carbon percentage in different coals

NOTE: % of volatile matter in coal = $\dfrac{\text{Loss in weight of the coal}}{\text{Weight of air-dried coal}} \times 100$

- If FD fans should have high V_b so as to rotate at high speed and handle large volume flow of air. Therefore, **centrifugal fans with backward-curved blading are normally used for FD fans.**
- The ID fans handle dust laden flue gases and so the blades are subjected to erosion by the fly ash. The erosion rate of blades is lower if the blade tip speed V_b is less and fan rotates at lower speeds. Therefore **centrifugal fans having forward-curved or flat blading are used for ID fans.** Low-speed fans with flat blades are used for particularly dirty or corrosive gases.

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OBJECTIVE BRAIN TEASERS

Q.1 In steam generators, a stoker acts as one of the following devices. What is this device?
(a) Air preheating device
(b) Steam superheating device
(c) Air superheating device
(d) Fuel feeding device

Q.2 A chimney of height 40 m has mean flue gas temperature of 327°C. The temperature of outside air is 30°C. The air-fuel ratio is 14.3. Draught produced in mm of water column is
(a) 20.26 mm H_2O (b) 21.42 mm H_2O
(c) 23.26 mm H_2O (d) 24.61 mm H_2O

Q.3 The expression for stoichiometric air required for combustion of coal having C, H, O and S is
(a) $4.32\left(2.67C+H-\frac{O}{8}+S\right)$
(b) $4.32(2.67C+8H+S-O)$
(c) $2.67C+8\left(H+\frac{O}{8}\right)+S$
(d) $2.67C+8\left(H-\frac{O}{8}\right)+S$

Q.4 A coal sample contains carbon, hydrogen and moisture in the ratio 3 : 1 : 1. It is burnt in dry air to find the HHV of 49.2 MJ/kg. The LHV of the coal sample if latent heat of water is 2260 kJ/kg is
(a) 48.296 MJ/kg (b) 44.68 MJ/kg
(c) 40.612 MJ/kg (d) 46.52 MJ/kg

Q.5 Choose the correct statements:
1. Coal oil mixture and coal water mixture are used as the boiler fuel.
2. Coal-water mixture is superior to coal oil mixture.
(a) 1 only (b) 1 and 2
(c) 2 only (d) None of these

Q.6 Consider the following statements regarding analysis of coal:
1. Proximate analysis of coal is done on mass basis.
2. Ultimate analysis of coal is done on volume basis.
3. Proximate analysis can be used to determine the mass fraction of fixed carbon in the coal.
4. Proximate analysis of coal does not require combustion of coal.

Which of the above statements are correct?
(a) 1 and 3 only (b) 1, 2 and 3 only
(c) 2 and 4 only (d) 1, 2, 3 and 4

Q.7 Which of the following is not an advantage of cyclone furnaces?
(a) Can burn poor grades of coal also
(b) Low ash content
(c) High NO_x formation
(d) No pulverization equipment required

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ANSWER KEY

1. (d) 2. (b) 3. (b) 4. (b) 5. (c)
6. (a) 7. (c)

HINTS & EXPLANATIONS

2. (b)

$$h = 353H\left[\frac{1}{T_1}-\left(\frac{m+1}{m}\right)\frac{1}{T_2}\right]$$

$$= 353 \times 40\left[\frac{1}{303} - \frac{14.3+1}{14.3} \times \frac{1}{600}\right]$$
$$= 21.42 \text{ mm } H_2O$$

4. (b)

Mass fraction of moisture,

$$M = \frac{1}{1+1+3} = 0.2$$

Mass fraction of hydrogen,

$$H = \frac{1}{1+1+3} = 0.2$$

$$\text{LHV} = \text{HHV} - (M + 9H)h_{fg}$$
$$\text{LHV} = 49.2 - (0.2 + 0.2 \times 9) \times 2.260$$
$$= 49.2 - (2) \times 2.260$$
$$= 49.2 - 4.52 = 44.68 \text{ MJ/kg}$$

6. (a)

- Both proximate and ultimate analysis of coal are done on mass basis.
- Proximate analysis can be used to determine mass fraction of fixed carbon, moisture, volatile matter and ash.
- Proximate analysis also require combustion of coal.

7. (c)

Disadvantages of cyclone furnaces are:
(a) High power requirement
(b) High NO_x formation
(c) High forced draught fan pressure

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CONVENTIONAL BRAIN TEASERS

Q.1 Propane (C_3H_8) is used as a fuel in an engine with 30% excess air. Assuming complete combustion determine the composition of exhaust gases on mass basis. Atomic weights are C = 12, O = 16, N = 14, H = 1. Molar ratio of nitrogen to oxygen is 3.76.

Solution:

$$C_3H_8 + x(O_2 + 3.76N_2) \rightarrow aCO_2 + bH_2O + cN_2$$

Carbon balance: $a = 3$

H balance: $8 = 2b \quad \text{or} \quad b = 4$

O balance: $2x = 2a + b = 2 \times 3 + 4 = 10 \quad \text{or} \quad x = 5$

N balance: $7.52x = 2c$

$7.52 \times 5 = 2c \quad \text{or} \quad c = 18.8$

Now as 30% excess air is used

$$C_3H_8 + 1.3 \times 5\,(O_2 + 3.76\,N_2) = 3CO_2 + 4H_2O + cO_2 + d\,N_2$$

Now again O balance gives us

$$1.3 \times 5 \times 2 = 3 \times 2 + 4 + 2c$$
$$\Rightarrow \quad c = 1.5$$

Again N balance, $1.3 \times 5 \times 3.76 \times 2 = 2d$

$$d = 24.44$$

Mass analysis,

$$CO_2 = 3 \times 44 = 132 = \frac{132}{936.32} \times 100 = \mathbf{14.09\%}$$
$$H_2O = 4 \times 18 = 72 = \frac{72 \times 100}{936.32} = \mathbf{7.69\%}$$
$$O_2 = 1.5 \times 32 = 48 = \frac{48 \times 100}{936.32} = \mathbf{5.12\%}$$
$$N_2 = 24.44 \times 28 = 684.32 = \frac{684.32 \times 100}{936.32} = \mathbf{73.08\%}$$

CHAPTER

3

Analysis of Steam Cycles

3.1 INTRODUCTION

Steam power plants work on the basis of some thermodynamic cycle, such as Carnot cycle and Rankine cycle. Carnot cycle is an ideal and most efficient cycle but is not practically feasible. Coal based power stations are using Rankine cycle.

A steam power plant continuously converts the chemical energy of the fossil fuels (coal, oil), fissile fuels (Uranium, thorium) into mechanical energy and ultimately into electrical energy. The working substance is water which is sometimes in the liquid phase and sometimes in the vapour phase.

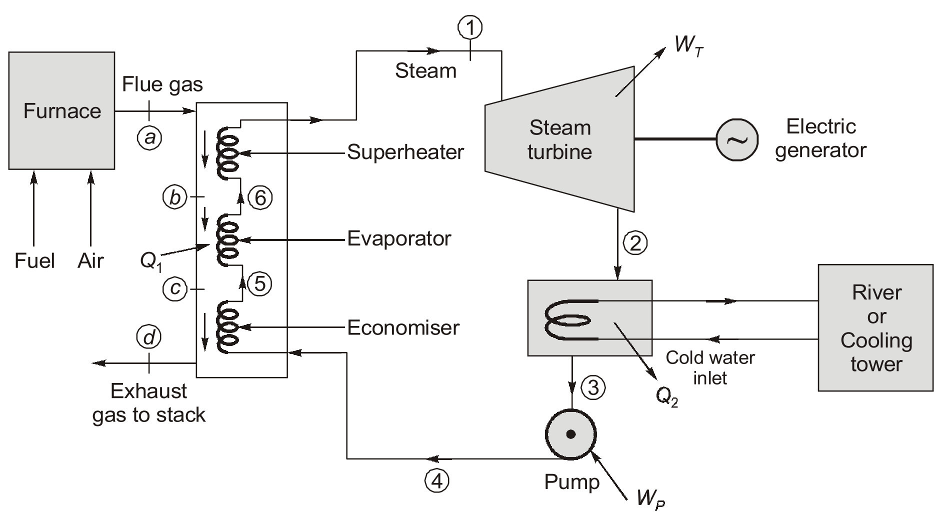


Figure: Simple steam power plant

3.2 CARNOT CYCLE

This cycle was proposed by Sadi Carnot. Under Carnot cycle, the working substance receives heat at temperature and rejects at another temperature. The cycle consists of **two isothermal** processes and **two reversible adiabatic** processes. This cycle is of great value to heat power theory although it has not been possible to construct a practical plant on this cycle. It has high thermodynamics efficiency. It is a standard of comparison for all other cycles.

Process 1–2: Isentropic (reversible adiabatic) expansion.

Process 2–3: Reversible isothermal heat rejection

Process 3–4: Isentropic (reversible adiabatic) compression

Process 4–1: Reversible isothermal heat addition

All the above processes of Carnot cycle are reversible hence the entire cycle is also reversible. The same can also be represented by a heat engine which operates between two thermal reservoirs maintained at temperature T_1 and T_2 and produces the work W.

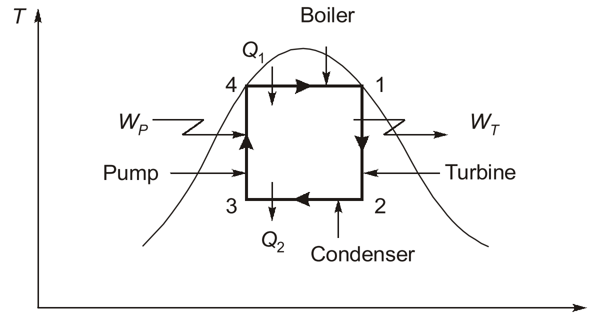


Figure: Carnot cycle

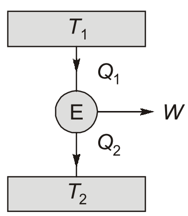


Figure: Heat engine

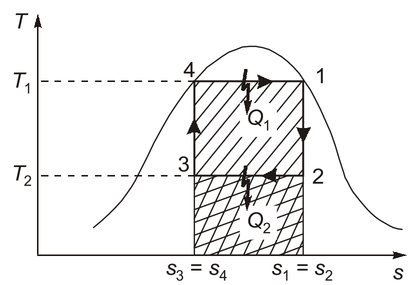


Figure: Heat interaction in Heat engine

The single line hatched area enclosed by points 1, 2, 3, 4 represents the net heat ($Q_1 - Q_2$) or net work ($W_T - W_P$) interaction, and the double line or crossed hatched area represents heat rejection, (Q_2).

For a substance undergoing a cyclic change, cyclic integral of work is equal to the cyclic integral of heat. Thus,

$W_T - W_P = Q_1 - Q_2$, and efficiency (η) can be represented by

$$\eta = \frac{\text{Net work}}{\text{Heat supplied}} = \frac{W_T - W_P}{Q_1} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1} = 1 - \frac{T_2(s_2 - s_3)}{T_1(s_1 - s_4)} = 1 - \frac{T_2}{T_1}$$

Since the area under a process on T-s diagram represents the heat interaction.

3.2.1 Limitations of Carnot Cycle

1. **Termination of condensation process** is not practically feasible at point 3 from where compression leads to point 4 on saturation line, *i.e.*, water in saturated condition and needs only latent heat for conversion into vapour.
2. During compression of the **mixture of steam and water** in the pump from point 3 to point 4, steam is getting condensed and vanishes at the end of compression. When steam gets converted into water, a large difference in specific volume causes cavitation over the impellers. The cavitation damage the impeller due to which impeller requires frequent replacement.
3. Any pump cannot suck the mixture of water and its vapour at state point 3 and deliver saturated liquid at state point 4, which is the need of Carnot cycle.
4. If exhaust steam from turbine is completely cooled in condenser, then transfer of heat at constant temperature and infinite pressure gradient is not possible. **Addition of heat at constant temperature is possible only within the dome**. Outside the dome, i.e., either in sub-cooled region or superheat region this is not possible.

OBJECTIVE BRAIN TEASERS

Q.1 In Rankine cycle power plant

1. Regeneration doesn't effect efficiency.
2. While reheating is done, the change in efficiency depends on reheating pressure.
3. Reheating always improves cycle efficiency upto 1.2 to 1.35 times.

Which of these statement(s) is/are correct?

(a) 1 only (b) 2 only
(c) 1 and 2 only (d) 2 and 3 only

Q.2 In Rankine cycle, pump work is often neglected because

(a) Pressure rise is not much in pump
(b) Pump is driven by external power source
(c) Specific volume of water is less that of vapour
(d) All of the above

Q.3 Terminal temperature difference for closed water heat is defined as

(a) (saturation temperature of bled steam) – (exit water temperature)
(b) (entry temperature of steam) – (exit water temperature)
(c) (exit temperature water of condensate) – (entry temperature of condensate water)
(d) None of these

Q.4 The reheat factor for steam turbines is defined as ratio of

(a) cumulative enthalpy drop to isentropic enthalpy drop
(b) isentropic enthalpy drop to cumulative enthalpy drop
(c) adiabatic enthalpy drop to total enthalpy drop
(d) input velocity to output velocity

Q.5 A steam turbine power plant has a net turbine power output of 2 MW with a net turbine heat rate of 2.5. The mass of coal (C.V. = 50 MJ/kg) required to be burnt every hour, if the boiler efficiency is 70%, is

(a) 46.2 kg (b) 36 kg
(c) 51.4 kg (d) 25.2 kg

Q.6 In a dual pressure steam turbine, steam enters with an enthalpy of 3200 kJ/kg at higher pressure. One fourth of the total steam enters at lower pressure with an enthalpy of 2600 kJ/kg. Steam exits the turbine with an enthalpy of 2100 kJ/kg. If work produced by the turbine is 2850 kW, the mass of steam at exit of turbine is

(a) 4.2 kg/s (b) 4 kg/s
(c) 2.92 kg/s (d) 3 kg/s

Q.7 Consider the steam power plant operating on a simple ideal Rankine cycle. Pump work input is 20 kJ/kg and turbine work output is 1250 kJ/kg. Heat supplied in boiler is 3500 kJ/kg. If the turbine and the pump have each 80% efficiency, for a mass flow rate of 20 kg/s, the net power output and thermal efficiency of the cycle will be

(a) 16.5 MW, 39.25% (b) 24.5 MW, 27.35%
(c) 19.5 MW, 27.85% (d) 17.5 MW, 24.52%

Q.8 Consider the following statements regarding the desirable characteristics of working fluid in a vapour power cycle

1. The fluid should have a high critical temperature.
2. The saturation pressure at the temperature of heat rejection should be above atmospheric pressure.
3. The saturation vapour line of the T-s diagram should be steep.
4. It should have large enthalpy of evaporation.

Which of the above statements are correct?

(a) 1, 2 and 3 (b) 2, 3 and 4
(c) 1, 3 and 4 (d) 1, 2, 3 and 4

Q.9 The enthalpy of steam entering a turbine in a Rankine cycle is 3200 kJ/kg. The enthalpy after isentropic expansion is 2400 kJ/kg and the enthalpy at the end of actual expansion is 2500 kJ/kg. What is the turbine efficiency?

(a) 75% (b) 80%
(c) 84% (d) 87.5%

3. Quality of steam at the turbine exhaust decreases for fixed maximum temperature.
4. Fraction of heat added in the evaporator increases.

Select the correct answer using the codes given below:
(a) 3 and 4 (b) 2 and 3
(c) 2, 3 and 4 (d) 1, 2 and 3

Q.18 Turbine blades erosion in its later stages in a steam power plant can be prevented by
(a) Reducing condenser pressure
(b) Increasing boiler pressure
(c) Reheating
(d) All of the above

ANSWER KEY

1. (b)	2. (c)	3. (a)	4. (a)	5. (c)
6. (d)	7. (c)	8. (d)	9. (d)	10. (a)
11. (d)	12. (c)	13. (c)	14. (c)	15. (b)
16. (c)	17. (b)	18. (c)		

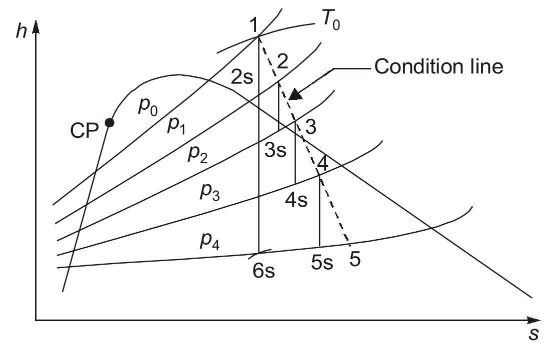
HINTS & EXPLANATIONS

1. (b)
Statement 1 and 3 are incorrect.
- In Rankine cycle, regeneration results in higher efficiency because average temperature of heat addition in the boiler increases.
- By reheating, the efficiency increase only when the optimum reheat pressure is 0.20 to 0.25 of initial steam pressure.

2. (c)
In Rankine cycle, pump work is neglected because specific volume of water is less than that of vapour ($v_f << v_g$).

3. (a)
Terminal temperature difference for closed water heat is the difference of saturation temperature of bled steam and the exit water temperature.

4. (a)



$$\text{Reheat factor} = \frac{\text{Cumulative enthalpy drop}}{\text{Isentropic enthalpy drop}}$$

$$= \frac{(h_1 - h_{2s}) + (h_2 - h_{3s}) + (h_3 - h_{4s}) + (h_4 - h_{5s})}{h_1 - h_{6s}}$$

5. (c)

$$\dot{w}_{net} = 2 \text{ MW}$$

$$\dot{Q}_{in} = \text{NTHR} \times \dot{w}_{net}$$

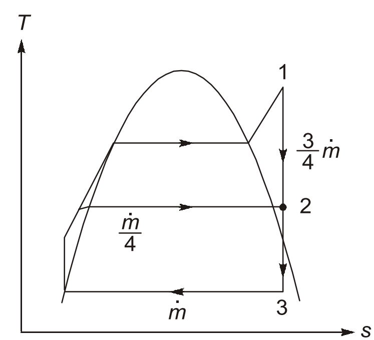
$$= 2.5 \times 2 = 5 \text{ MW}$$

$$\dot{m}_f \times C.V. \times \eta_B = \dot{Q}_{in}$$

$$\dot{m}_f = \frac{5}{50 \times 7} \times 3600 \text{ kg/hr}$$

$$= 51.428 \text{ kg/hr}$$

6. (d)



$$\dot{W} = \frac{\dot{m}}{4}(h_2 - h_3) + \frac{3}{4}\dot{m}(h_1 - h_3)$$

$$2850 = \frac{\dot{m}}{4}(2600 - 2100) + \frac{3}{4}\dot{m}(3200 - 2100)$$

$$\dot{m} = 3 \text{ kg/s}$$

CONVENTIONAL BRAIN TEASERS

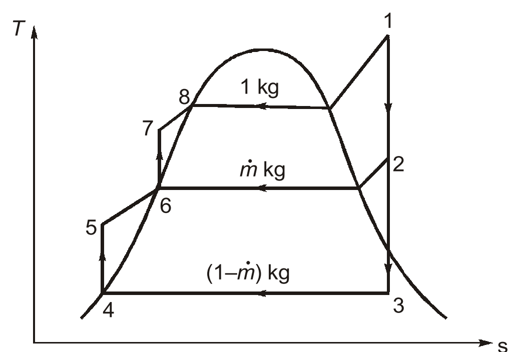
Q.1 Show that the maximum efficiency of a Rankine cycle with regeneration is $\eta = \dfrac{\alpha^2 + 4\alpha\beta}{(\alpha+2\beta)^2}$, where $\beta = h - h_f$ = Constant, α = Total enthalpy rise of feed water.

Solution:

Since, m kg of steam is extracted from the turbine for each kg of steam entering it to heat the feed water from state 5 to state 6, so that by energy balance.

$$\dot{m}(h_2 - h_6) = (1-\dot{m})(h_6 - h_5)$$

$$\dot{m} = \frac{h_6 - h_5}{h_2 - h_5} = \frac{h_6 - h_4}{h_2 - h_4} \qquad (\because h_4 = h_5)$$



Therefore, the thermal efficiency of the cycle is

$$\eta = 1 - \frac{(1-\dot{m})(h_3 - h_4)}{h_1 - h_6} = 1 - \frac{\left(1 - \dfrac{h_6 - h_5}{h_2 - h_4}\right)(h_3 - h_4)}{h_1 - h_6}$$

$$= 1 - \frac{(h_2 - h_6)(h_3 - h_4)}{(h_2 - h_4)(h_1 - h_6)} \qquad \text{... (i)}$$

Now, $\beta = h_1 - h_f = h_1 - h_4$ = Constant

and α = Total enthalpy rise of feedwater = $h_8 - h_4$

Let the enthalpy rise of feed water in heater $(\gamma) = h_6 - h_4$

Since, $\beta = h - h_f$,

which is constant that means β could be, $h_2 - h_6$ or $h_1 - h_8$ or $h_3 - h_4$ also.

Thus, $h_2 - h_4 = h_2 - h_6 + h_6 - h_4 = \beta + \gamma$

and $h_1 - h_6 = h_1 - h_8 + h_8 - h_4 + h_4 - h_6 = \beta + \alpha + \gamma$

Now, equation (i) becomes, $\eta = 1 - \dfrac{(\beta)(\beta)}{(\beta+\gamma)(\beta+\alpha-\gamma)}$