Unit -2

Vapour Power Cycles or Phase change cycle

CARNOT CYCLE

Figure shows a Carnot cycle on T-s and p-V diagrams. It consists of (I) two constant pressure operations (4-1) and (2-3) and (ii) two frictionless adiabatic (1-2) and (3-4). These operations are discussed below:

1. Operation (4-1). 1 kg of boiling water at temperature T1 is heated to form wet steam of dryness fraction x1. Thus heat is absorbed at constant temperature T1 and pressure p1 during this operation.

2. Operation (1-2). During this operation steam is expanded isentropically to temperature T2 and pressure p2. The point '2' represents the condition of steam after expansion.

3. Operation (2-3). During this operation heat is rejected at constant pressure p2 and temperature T2. As the steam is exhausted it becomes wetter and cooled from 2 to 3.

4. Operation (3-4). In this operation the wet steam at '3' is compressed isentropically till the steam regains its original state of temperature T1 and pressure p1. Thus cycle is completed.

Refer T-s diagram:

Heat supplied at constant temperature T1 [operation (4-1)] = area 4-1-b-a = T1 (s1 – s4) or T1 (s2 – s3).

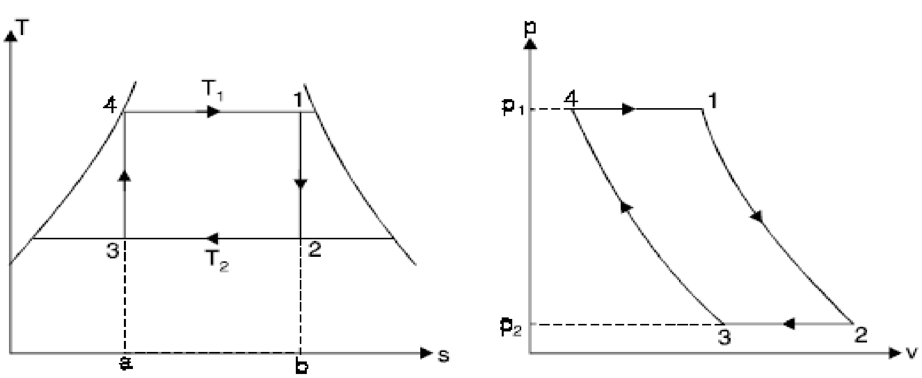


Fig. 1 Carnot cycle on T-s and p-V diagrams

Heat rejected at constant temperature T2 (operation 2-3) = area 2-3-a-b = T2 (s2 – s3).

Limitations of Carnot Cycle

Though Carnot cycle is simple (thermodynamically) and has the highest thermal efficiency for given values of T1 and T2, yet it is extremely difficult to operate in practice because of the following reasons:

1. It is difficult to compress a wet Vapour isentropically to the saturated state as required by the process 3-4.

2. It is difficult to control the quality of the condensate coming out of the condenser so that the state '3' is exactly obtained.

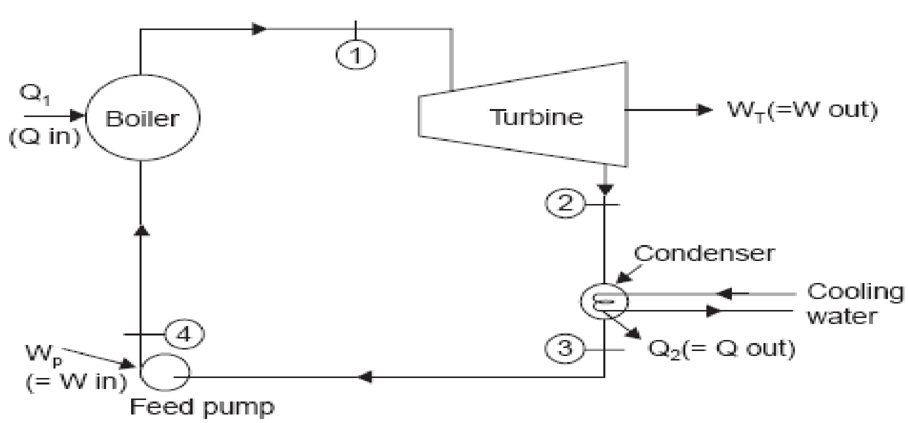
3. The efficiency of the Carnot cycle is greatly affected by the temperature T1 at which heat is transferred to the working fluid. Since the critical temperature for steam is only 374°C, therefore, if the cycle is to be operated in the wet region, the maximum possible temperature is severely limited.

4. The cycle is still more difficult to operate in practice with superheated steam due to the necessity of supplying the superheat at constant temperature instead of constant pressure (as it is customary).

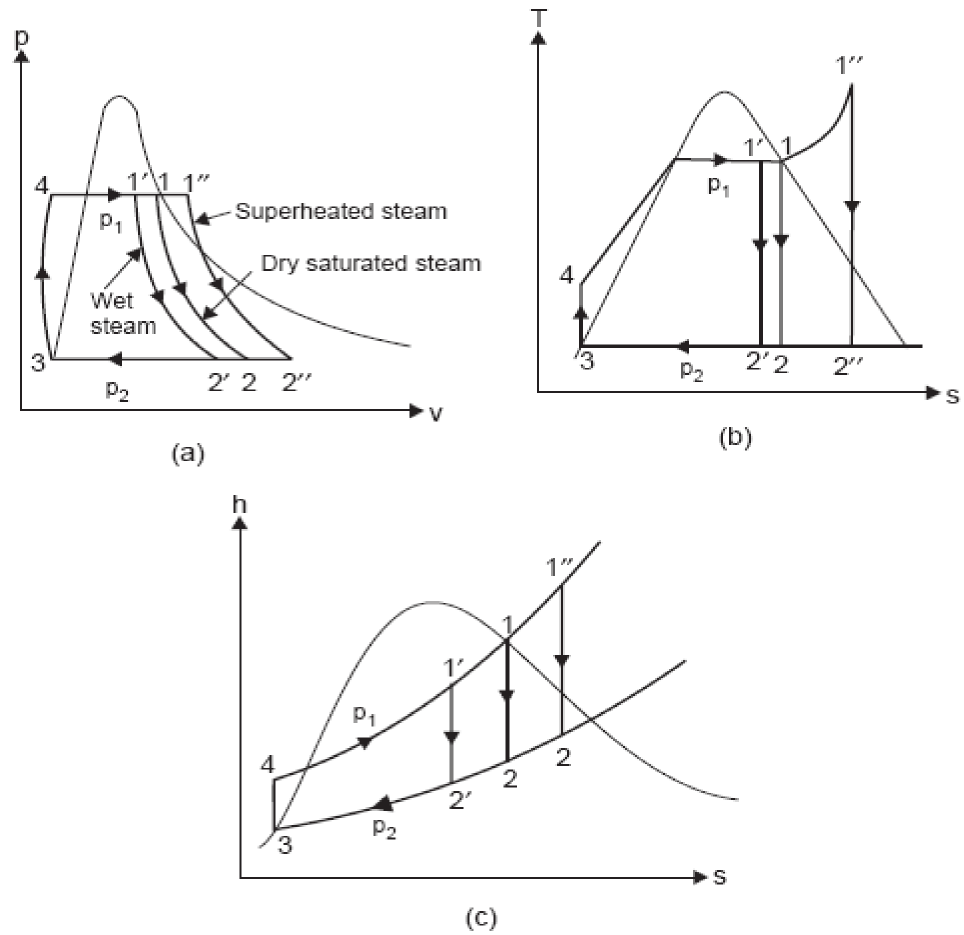
In a practical cycle, limits of pressure and volume are far more easily realised than limits of temperature so that at present no practical engine operates on the Carnot cycle, although all modern cycles aspire to achieve it.

RANKINE CYCLE

Rankine cycle is the theoretical cycle on which the steam turbine (or engine) works.



Rankine cycle.



(a) p-v diagram ; (b) T-s diagram ; (c) h-s diagram for Rankine cycle.

(b) The Rankine cycle is shown in Fig. It comprises of the following *processes* :
(c) **Process 1-2 :** Reversible adiabatic expansion in the turbine (or steam engine).
(d) **Process 2-3 :** Constant-pressure transfer of heat in the condenser.
(e) **Process 3-4 :** Reversible adiabatic pumping process in the feed pump.
(f) **Process 4-1 :** Constant-pressure transfer of heat in the boiler.
(g) Fig. 12.3 shows the Rankine cycle on *p-v*, *T-s* and *h-s* diagrams (when the saturated steam
(h) enters the turbine, the steam can be wet or superheated also).
(i) **Considering 1 kg of fluid :**
(j) Applying *steady flow energy equation* (S.F.E.E.) to boiler, turbine, condenser and pump :
(k) (*i*) **For boiler** (as control volume), we get

Comparison between Rankine Cycle and Carnot Cycle-

The following points are worth noting :

(i) Between the same temperature limits Rankine cycle provides a higher specific work output than a Carnot cycle, consequently Rankine cycle requires a smaller steam flow rate resulting in smaller size plant for a given power output. However, Rankine cycle calls for higher rates of heat transfer in boiler and condenser.

(ii) Since in Rankine cycle only part of the heat is supplied isothermally at constant higher temperature T1, therefore, its efficiency is lower than that of Carnot cycle. The efficiency of the Rankine cycle will approach that of the Carnot cycle more nearly if the superheat temperature rise is reduced.

(iii) The advantage of using pump to feed liquid to the boiler instead to compressing a wet vapour is obvious that the work for compression is very large compared to the pump.

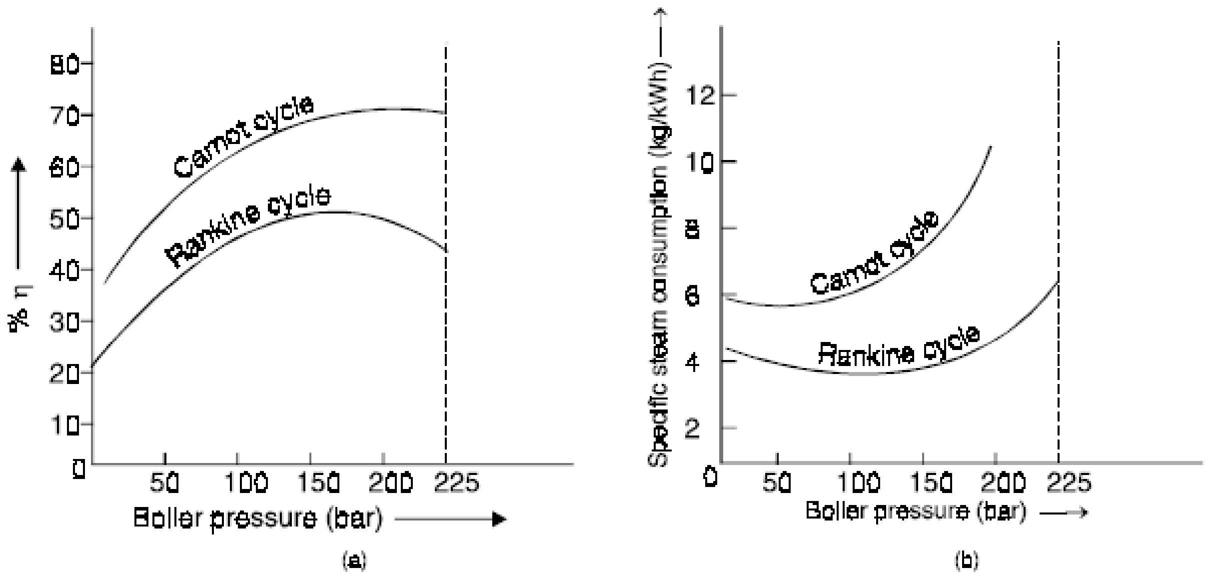
Fig. shows the plots between efficiency and specific steam consumption against boiler pressure for Carnot and ideal Rankine cycles.

Effect of Operating Conditions on Rankine Cycle Efficiency

The Rankine cycle efficiency can be improved by:

(i) Increasing the average temperature at which heat is supplied.

(ii) Decreasing/reducing the temperature at which heat is rejected



This can be achieved by making suitable changes in the conditions of steam generation or condensation, as discussed below :

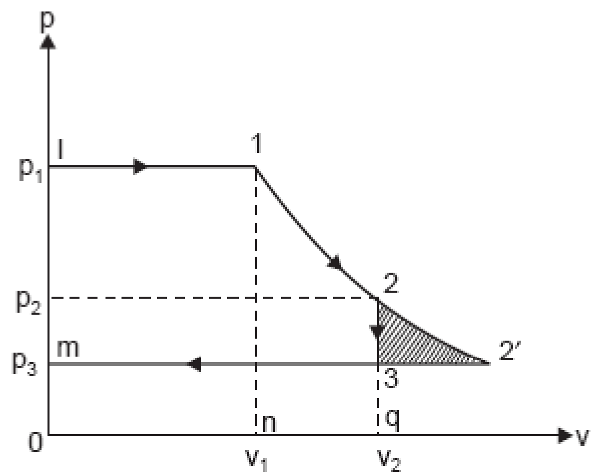
1. ***Increasing boiler pressure*****.** It has been observed that by increasing the boiler pressure (other factors remaining the same) the cycle tends to rise and reaches a maximum value at a boiler pressure of about 166 bar [Fig. (*a*)].

2. ***Superheating*****.** All other factors remaining the same, if the steam is superheated before allowing it to expand the Rankine cycle efficiency may be increased [Fig. (*b*)]. The use of superheated steam also ensures longer turbine blade life because of the absence of erosion from high velocity water particles that are suspended in wet vapour.

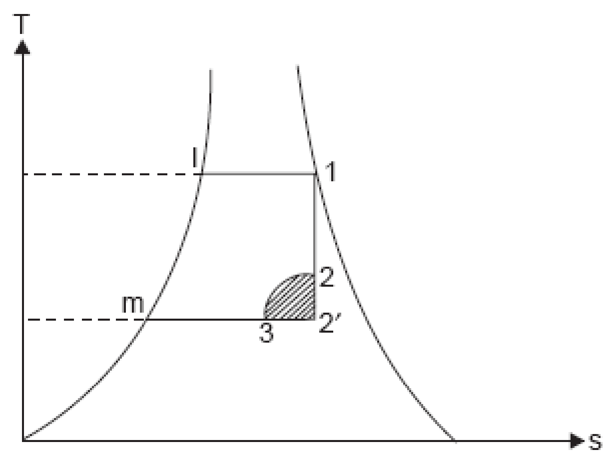
3. ***Reducing condenser pressure*****.** The thermal efficiency of the cycle can be amply improved by reducing the condenser pressure [Fig. 12.5 (*c*)] (hence by reducing the temperature at which heat is rejected), especially in high vacuums. But the increase in efficiency is obtained at the increased cost of condensation apparatus

MODIFIED RANKINE CYCLE

Figures show the modified Rankine cycle on p-V and T-s diagrams (neglecting pump work) respectively. It will be noted that p-V diagram is very narrow at the toe i.e., point ‘2’’ and the work obtained near to e is very small. In fact this work is too inadequate to overcome friction (due to reciprocating parts) even. Therefore, the adiabatic is terminated at ‘2’ ; the pressure drop decreases suddenly whilst the volume remains constant. This operation is represented by the line 2-3. By this doing the stroke length is reduced ; in other words the cylinder dimensions reduce but at the expense of small loss of work (area 2-3-2’) which, however, is negligibly small.



. *p-V* diagram of Modified Rankine Cycle.

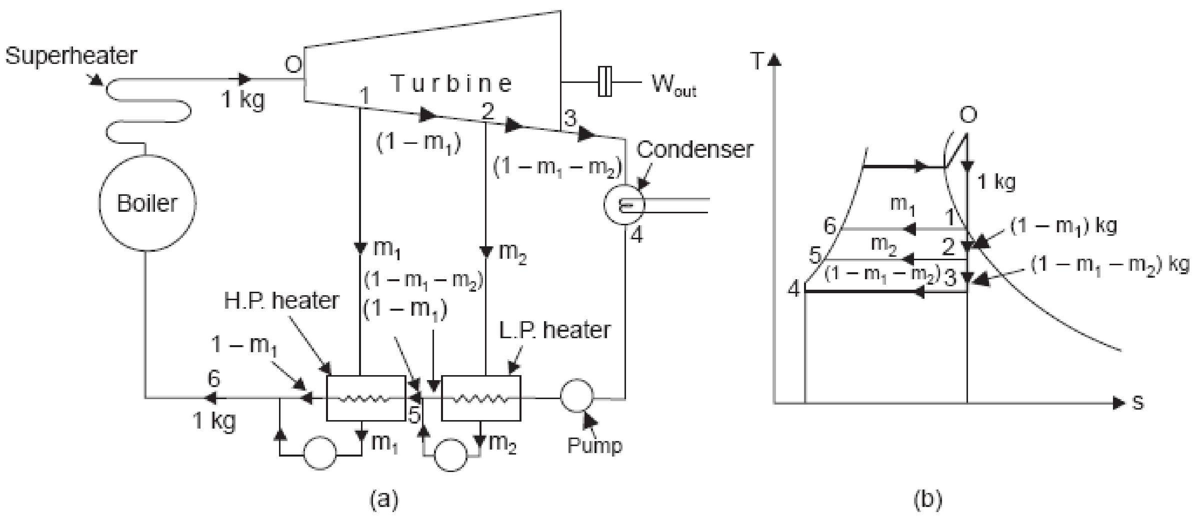


. *T-s* diagram of Modified Rankine cycle.

REGENERATIVE CYCLE

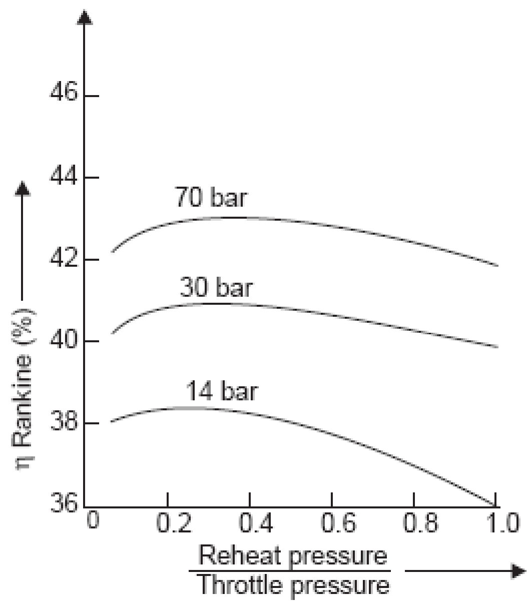
In the Rankine cycle it is observed that the condensate which is fairly at low temperature has an irreversible mixing with hot boiler water and this results in decrease of cycle efficiency. Methods are, therefore, adopted to heat the feed water from the hot well of condenser irreversibly by interchange of heat within the system and thus improving the cycle efficiency. This heating method is called regenerative feed heat and the cycle is called regenerative cycle. The principle of regeneration can be practically utilised by extracting steam from the turbine at several locations and supplying it to the regenerative heaters. The resulting cycle is known as regenerative or bleeding cycle. The heating arrangement comprises of : (i) For medium capacity turbines—not more than 3 heaters ; (ii) For high pressure high capacity turbines—not more than 5 to 7 heaters ; and (iii) For turbines of super critical parameters 8 to 9 heaters. The most advantageous condensate heating temperature is selected depending on the turbine throttle conditions and this determines the number of heaters to be used. The final condensate heating temperature is kept 50 to 60°C below the boiler saturated steam temperature so as to prevent evaporation of water in the feed mains following a drop in the boiler drum pressure. The conditions of steam bled for each heater are so selected that the temperature of saturated steam will be 4 to 10°C higher than the final condensate temperature diagrammatic layout of a condensing steam power plant in which a surface condenser is used to condense all the steam that is not extracted for feed water heating.

The turbine is double extracting and the boiler is equipped with a superheater. The cycle diagram (T-s) would appear as shown in Fig.

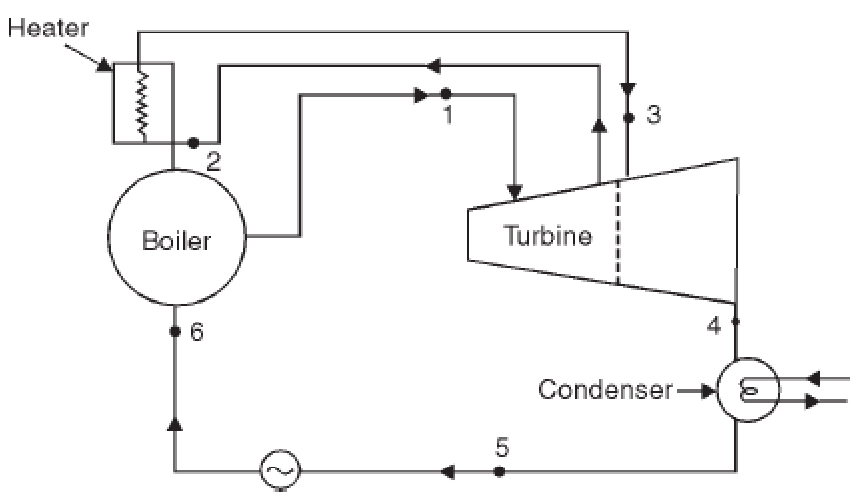


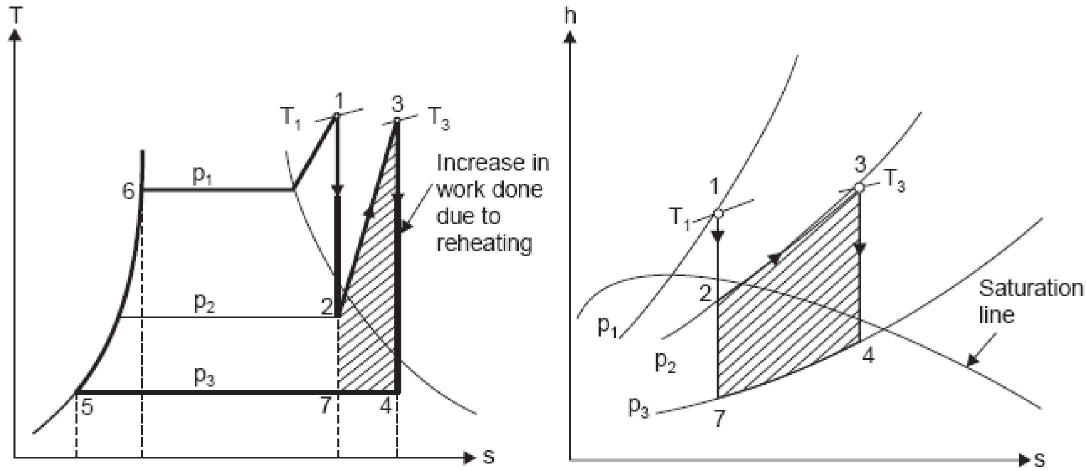
REHEAT CYCLE

For attaining greater thermal efficiencies when the initial pressure of steam was raised beyond 42 bar it was found that resulting condition of steam after, expansion was increasingly wetter and exceeded in the safe limit of 12 per cent condensation. It, therefore, became necessary to reheat the steam after part of expansion was over so that the resulting condition after complete expansion fell within the region of permissible wetness. The reheating or resuperheating of steam is now universally used when high pressure and temperature steam conditions such as 100 to 250 bar and 500°C to 600°C are employed for throttle. For plants of still higher pressures and temperatures, a double reheating may be used. In actual practice reheat improves the cycle efficiency by about 5% for a 85/15 bar cycle. A second reheat will give a much less gain while the initial cost involved would be so high as to prohibit use of two stage reheat except in case of very high initial throttle conditions. The cost of reheat equipment consisting of boiler, piping and controls may be 5% to 10% more than that of the conventional boilers and this additional expenditure is justified only if gain in thermal efficiency is sufficient to promise a return of this investment. Usually a plant with a base load capacity of 50000 kW and initial steam pressure of 42 bar would economically justify the extra cost of reheating. The improvement in thermal efficiency due to reheat is greatly dependent upon the reheat pressure with respect to the original pressure of steam.



Condenser pressure : 12.7 mm Hg
Temperature of throttle and heat : 427°C

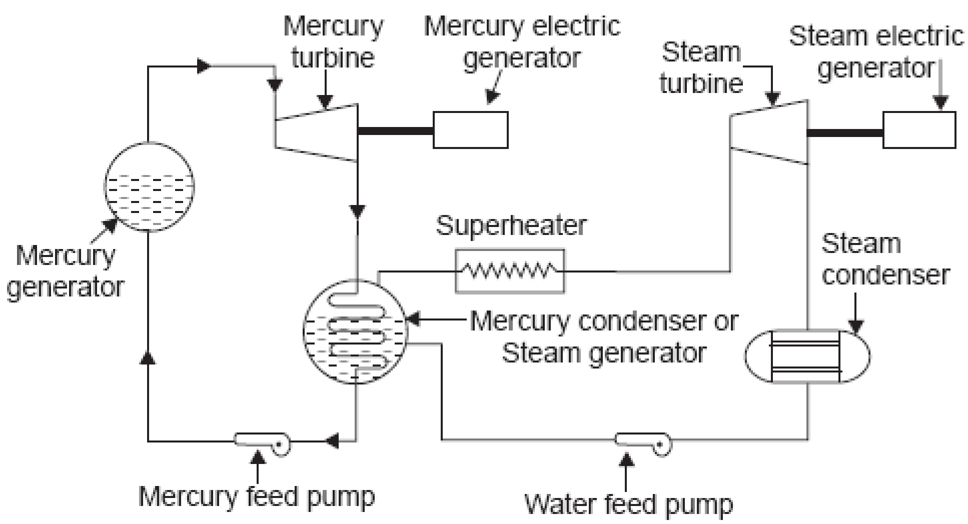




Thermal efficiency *without reheating* is

$$\eta_{thermal} = \frac{h_1 - h_7}{h_1 - h_{f_4}} \quad (\because \quad h_{f_4} = h_{f_7})$$

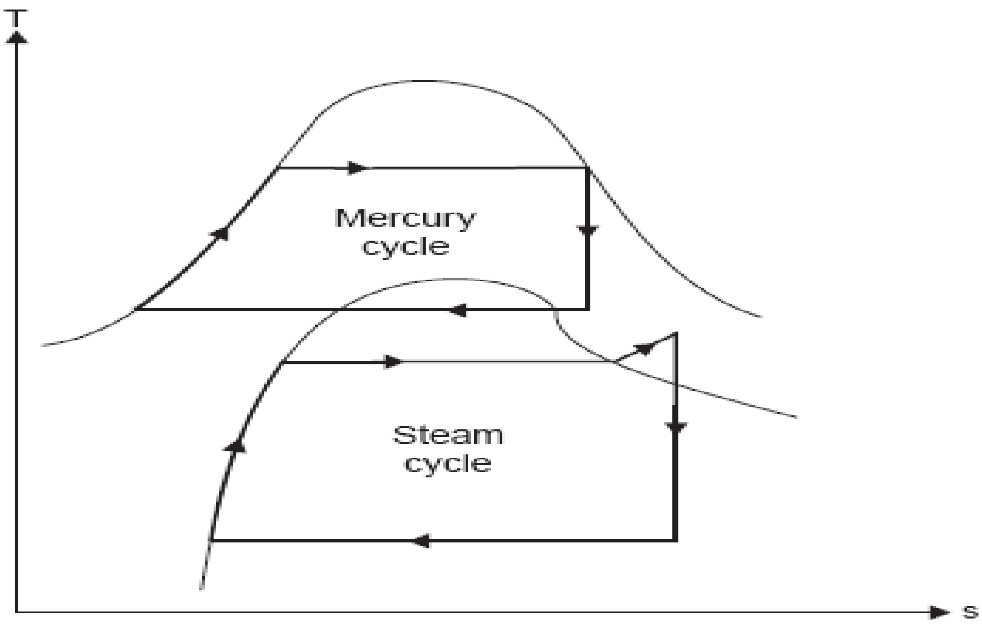
BINARY VAPOUR CYCLE



<u>**BINARY VAPOUR CYCLE**</u>

Overall efficiency of the binary cycle is given by

$$\eta = \frac{\text{Work done}}{\text{Heat supplied}} = \frac{W_t}{h_t} = \frac{mW_{hg} + W_s}{mh_{hg_1}}$$



The thermal efficiency of the steam cycle is given by

$$\eta_s = \frac{W_s}{h_s} = \frac{h_{s_1} - h_{s_2}}{h_{s_1}} = \frac{h_{s_1} - h_{s_2}}{m h_{hg_2}}$$

THEORETICAL QUESTIONS

1. Explain the various operation of a Carnot cycle. Also represent it on a T-s and p-V diagrams.

2. Describe the different operations of Rankine cycle. Derive also the expression for its efficiency.

3. State the methods of increasing the thermal efficiency of a Rankine cycle.

4. Explain with the help of neat diagram a ‘Regenerative Cycle’. Derive also an expression for its thermal efficiency.

5. State the advantages of regenerative cycle/simple Rankine cycle.

6. Explain with a neat diagram the working of a Binary Vapour cycle.

NUMERICAL QESTION:-

1. A simple Rankine cycle works between pressure of 30 bar and 0.04 bar, the initial condition of steam being dry saturated, calculate the cycle efficiency, work ratio and specific steam consumption. [Ans. 35%, 0.997, 3.84 kg/kWh]

2. A steam power plant works between 40 bar and 0.05 bar. If the steam supplied is dry saturated and the cycle of operation is Rankine, find: (i) Cycle efficiency (ii) Specific steam consumption. [Ans. (i) 35.5%, (ii) 3.8 kg/kWh]

3. Compare the Rankine efficiency of a high pressure plant operating from 80 bar and 400°C and a low pressure plant operating from 40 bar 400°C, if the condenser pressure in both cases is 0.07 bar. [Ans. 0.391 and 0.357]

4. A steam power plant working on Rankine cycle has the range of operation from 40 bar dry saturated to 0.05 bar. Determine:

(i) The cycle efficiency (ii) Work ratio

(iii) Specific fuel consumption. [Ans. (i) 34.64%, (ii) 0.9957, (iii) 3.8 kg/kWh]

5. In a Rankine cycle, the steam at inlet to turbine is saturated at a pressure of 30 bar and the exhaust pressure is 0.25 bar. Determine:

(i) The pump work (ii) Turbine work

(iii) Rankine efficiency (IV) Condenser heat flow

(v) Dryness at the end of expansion.

Assume flow rate of 10 kg/s. [Ans. (i) 30 kW, (ii) 7410 kW, (iii) 29.2%, (iv) 17900 kW, (v) 0.763]

6. In a regenerative cycle the inlet conditions are 40 bar and 400°C. Steam is bled at 10 bar in regenerative heating. The exit pressure is 0.8 bar. Neglecting pump work determine the efficiency of the cycle.

[Ans. 0.296]

7. A turbine with one bleeding for regenerative heating of feed water is admitted with steam having enthalpy of 3200 kJ/kg and the exhausted steam has an enthalpy of 2200 kJ/kg. The ideal regenerative feed water heater is fed with 11350 kg/h of bled steam at 3.5 bar (whose enthalpy is 2600 kJ/h). The feed water (condensate from the condenser) with an enthalpy of 134 kJ/kg is pumped to the heater. It leaves the heater dry saturated at 3.5 bar. Determine the power developed by the turbine. [Ans. 16015 kW]

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