Rankine Cycle and Improvement in Rankine Efficiency

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Abstract— Rankine cycle is a closed system thermodynamic vapour power cycle used for the production of energy using various intermediate processes and predicts the performance of a steam engine and steam turbines. There are various factors that affect the Rankine cycle such as quality of steam, inlet pressure and temperature, exhaust steam conditions, etc. We will be discussing all these factors and various thermodynamic processes involved in working of the Rankine cycle. In this paper we will see about the working, efficiency of Rankine cycle and methods to improve Rankine Efficiency.

Keywords: Rankine Cycle, Pump, Turbines, Condenser, Boiler, Entropy, Enthalpy, Efficiency, Vapour, Steam

I. INTRODUCTION

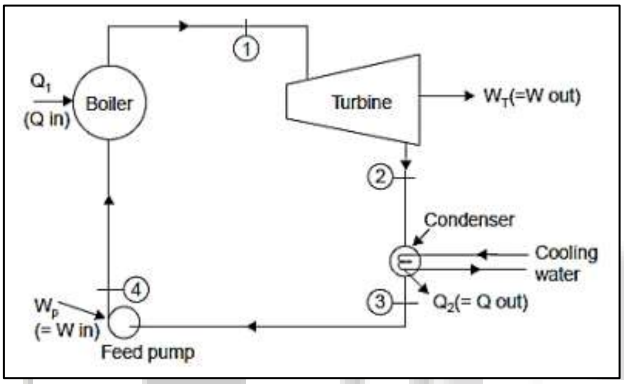

Fig. 1: Rankine Cycle

The Rankine cycle closely describes the process by which steam-operated heat engines commonly found in thermal power generation plants generate power. The heat sources used in these power plants are usually nuclear fission or the combustion of fossil fuels such as coal, natural gas, and oil, or concentrated solar power. The higher the temperature, the better efficiency. The working fluid in the Rankine cycle is steam. The steam is mainly passed in a dry saturated state. For increasing the efficiency of the Rankine cycle, now-a-days in modern steam plants superheated steam is also used. Rankine cycle is a closed loop wherein the working fluid is constantly circulated again and again without any mass transfer outside the thermodynamic boundary. The only limitation of the Rankine cycle is the maximum operating pressure and temperature. The operating pressure and temperature cannot be increased above critical pressure and critical temperature. The cycle consists of 2 isentropic and 2 isobaric processes. The efficiency depends on the temperature difference between the heat source and heat sink. In the process, the wet steam is passed through a boiler wherein it gets converted to a dry saturated steam and then is passed through the turbine. This saturated steam turns the turbine blades producing power output which is supplied to the necessary utilities. When the steam exits the turbine the pressure of the steam is dropped and also its dryness fraction. This steam is then passed through a condenser which cools the steam and further passes it to the feed pump. This feed pump again pumps the liquidated vapour back to the boiler and thus the cycle continues. The work output from the turbine is also used to drive the feed pump motor.

II. THERMODYNAMIC PROCESSES IN RANKINE CYCLE

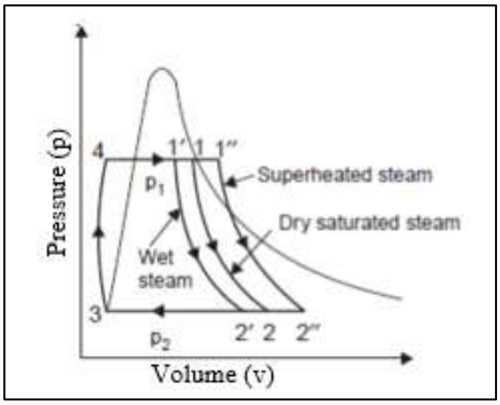

Fig. 2: p-v diagram of Rankine Cycle

- Process 1-2: Isentropic Expansion. (The dry saturated steam is passed through the turbine which produces work after expansion. At the exit of the turbine some condensation might occur.)
- Process 2-3: Constant Pressure Heat Rejection in Condenser. (The wet steam enters the condenser wherein it condenses into saturated liquid.)
- Process 3-4: Isentropic Compression. (The saturated liquid is pumped from a low pressure to a high pressure compressing the working fluid for which pump requires some amount of energy produced through the turbine.)
- Process 4-1: Constant Pressure Heat Addition in Boiler. (The compressed liquid is passed through the boiler wherein it is again converted into dry saturated steam.)

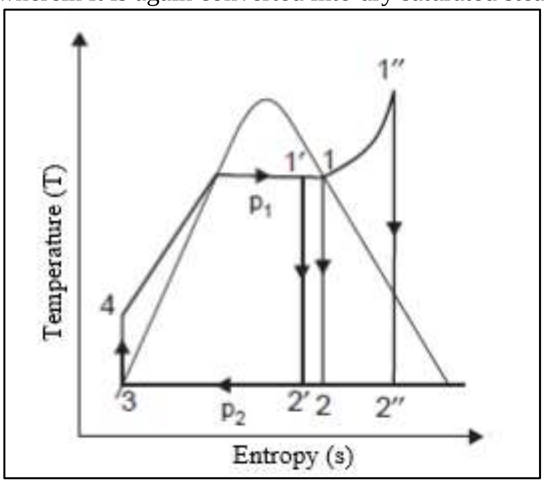

Fig. 3: T-s Diagram of Rankine Cycle

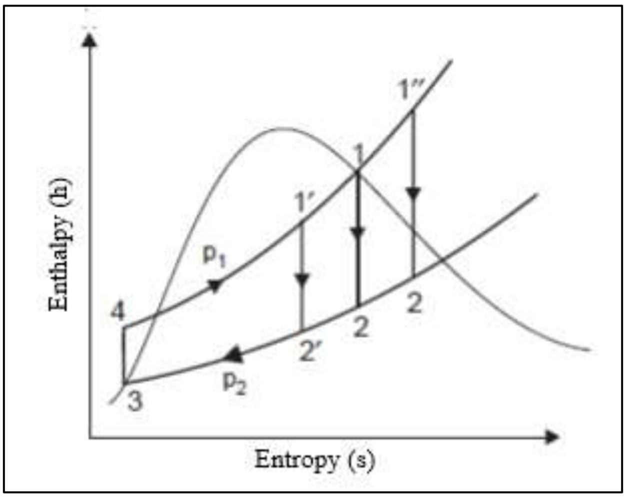

Fig. 4: h-s diagram of Rankine Cycle

Different qualities of steam used in the expansion processes are 1'-2', 1-2 and 1''-2''. The path 1'-2' indicates that the steam used is wet steam. The path 1-2 indicates that the steam used is dry saturated steam. Whereas the path 1''-2'' indicates that steam used is of superheated quality.

Quality of the steam greatly affects the efficiency of the Rankine cycle depending on whether it is wet steam, dry saturated steam or superheated steam.

III. Efficiency of Rankine Cycle

Let us consider 1kg of fluid for the operation of rankine cycle. Applying steady flow energy equation to turbine, condenser, pump and boiler:

A. *For boiler we get,*

$$h_{f_4} + Q_1 = h_1$$

$$Q_1 = h_1 - h_{f_4} \quad \text{.......... (1.1)}$$

B. *For turbine we get,*

$h_1 - W_T = h_2$ (where W_T is turbine work)

$$W_T = h_1 - h_2 \quad \text{............ (1.2)}$$

C. *For condenser we get,*

$$h_2 = Q_2 + h_{f_3}$$

$$\therefore \quad Q_2 = h_2 - h_{f_3} \quad \text{............(1.3)}$$

D. *For pump we get,*

$h_{f_3} + W_P = h_{f_4}$ (where W_P is pump work)

$$\therefore \quad W_P = h_{f_4} - h_{f_3} \quad \text{............(1.4)}$$

The efficiency of Rankine cycle is given by,

$$\eta_{rankine} = \frac{W_{net}}{Q_1} = \frac{W_T - W_P}{Q_1}$$

$$\therefore \eta_{rankine} = \frac{(h_1 - h_2)\ (h_{f4} - h_{f3})}{(h_1 - h_{f4})}$$

The feed pump term $(h_{f_4} - h_{f_3})$ is a very small term and is usually neglected, especially when boiler pressures are low. Hence at lower boiler pressures, we can write the efficiency as:

$$\eta_{rankine} = \frac{(h_1 - h_2)}{(h_1 - h_{f4})}$$

IV. Advantages of Rankine Cycle over Carnot Cycle

Between the same temperature limits, Rankine cycle provides a higher specific work output as compared to Carnot cycle. Rankine cycle requires smaller steam flow rate resulting in smaller size of power plant.

The advantage of using a feed pump in Rankine cycle rather than that of the compressor used in Carnot cycle is that the work required to compress a wet steam is very large than that of pump.

V. Improvement in Efficiency of Rankine Cycle

A. *Lowering the condenser pressure:*

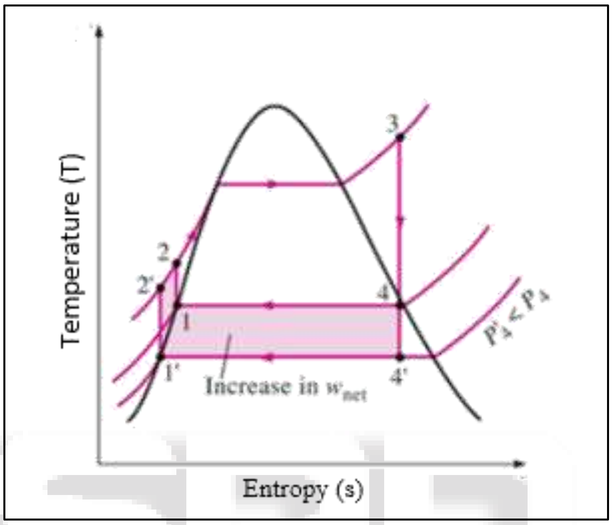

Fig. 5: T-s diagram when condenser pressure is lowered.

To take the advantage of increased efficiencies at lower pressures, some steam power plants operate well below atmospheric temperature. There is always a limit to which these pressures can be decreased. The only side effect is that the moisture content is the steam at the final stages of turbine increases due to lowering the condenser pressures.

B. *Superheating steam to high temperatures:*

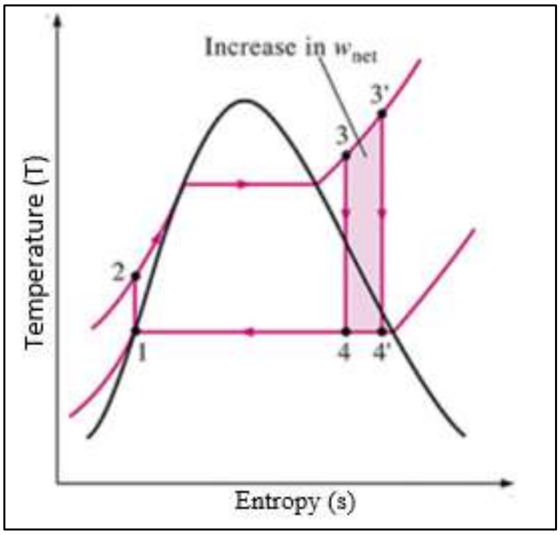

Fig. 6: T-s diagram when steam is superheated.

Both the net work and heat supplied is needed to be increased in order to superheat the steam to high temperatures. The temperature to which it can be superheated is limited by the existing metallurgical conditions. The present allowed maximum temperature of steam at the turbine inlet is 626ºC.

C. Increasing the boiler pressure:

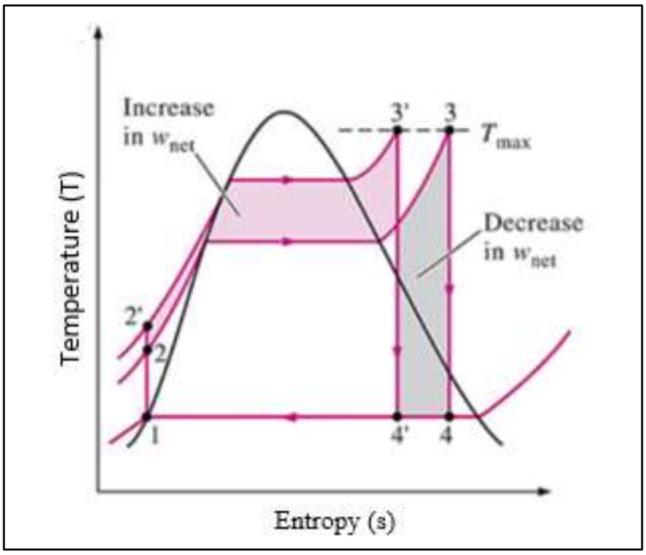

Fig. 7: T-s diagram when boiler pressure is increased.

The net work output of Rankine cycle is increased only to some extent because increasing the boiler pressure the cycle shifts to the left thereby increasing the moisture content at the exit of the turbine. This effect can be increased by reheating the steam. Now-a-days many power plants operate at supercritical pressure (P > 22Mpa) thereby increasing the efficiency.

VI. IDEAL REHEAT RANKINE CYCLE

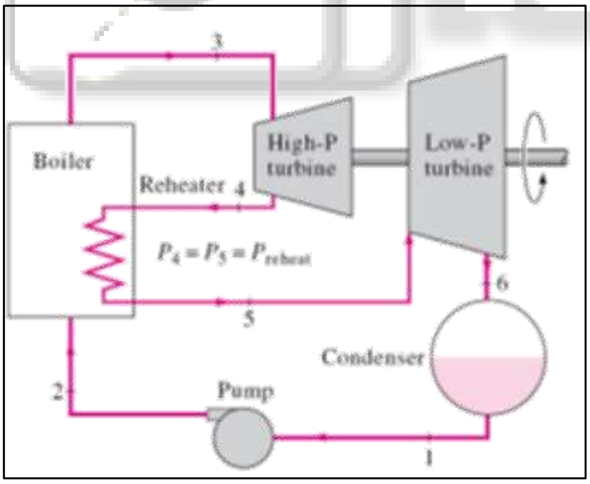

Fig. 8: Reheat Rankine cycle operated power plant setup.

A reheat process is considered for a simple Rankine cycle to reduce the moisture content at the turbine exit. The pressure at which the steam should be reheated and the net work output are to be determined. The exit of a high-pressure turbine is connected again with boiler and then it is passed to low pressure turbine where the reheated steam expands again. This in-turn increases the efficiency of Rankine Cycle.

A single reheat in the modern power plant increases the efficiency by 4 to 5% by increasing the average temperature at which the heat is transferred.

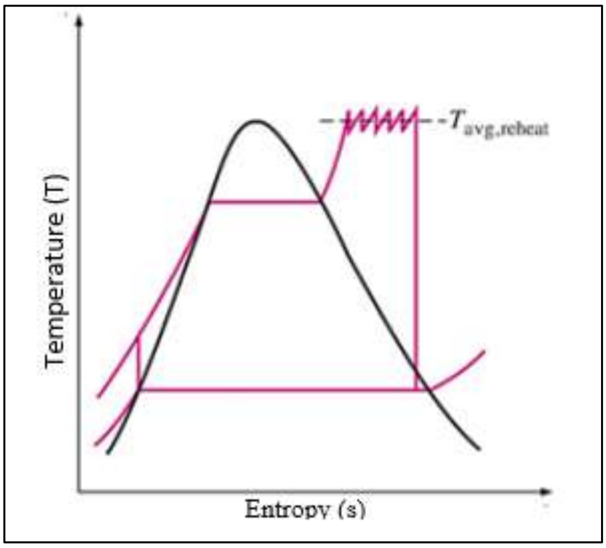

Fig. 9: Reheat Rankine cycle for multiple reheat stages.

The average temperature during the reheat process can be increased by increasing the number of expansion and reheat stages. As the stages increases the expansion and reheat processes approach isothermal process at the maximum temperature. The theoretical improvement of the second reheat is about half of that which results from single reheat.

The optimum reheat pressure is about one-fourth of the maximum cycle pressure.

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