POWER PLANT STEAM CYCLE THEORY

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Contents

Summary

The Carnot cycle is an ideal thermodynamic cycle based on the laws of thermodynamics. It indicates the maximum efficiency of a heat engine when operating between given temperatures of heat acceptance and heat rejection. The Rankine cycle is also an ideal cycle operating between two temperature limits but it is based on the principle of receiving heat by evaporation and rejecting heat by condensation.

The working fluid is water-steam. In steam driven thermal power plants this basic cycle is modified by incorporating superheating and reheating to improve the performance of the turbine.

The Rankine cycle with its modifications suggests the best efficiency that can be obtained from this two phase thermodynamic cycle when operating under given temperature limits but its efficiency is less than that of the Carnot cycle since some heat is added at a lower temperature.

The efficiency of the Rankine cycle can be improved by regenerative feedwater heating where some steam is taken from the turbine during the expansion process and used to preheat the feedwater before it is evaporated in the boiler.

In the ideal case with complete preheating in an infinite number of steps, the basic Rankine cycle without modifications approaches the Carnot cycle. Heat addition occurs

only at the highest temperature and heat rejection only at the lowest temperature as with the Carnot cycle.

Departures from the ideal situation described above are due to fluid friction in the system, particularly the turbine, and heat transfer across finite temperature differences in the feedwater heaters. These degrade the efficiency below that indicated by calculations based on the Rankine cycle under ideal conditions.

Friction in the turbine can be defined in terms of the actual work done and the ideal work that could be done in the turbine if there were no friction.

This is known as the internal efficiency of the turbine and should not be confused with the thermal cycle efficiency.

Under part load conditions the steam entering the turbine is partially throttled to reduce its flow. This has an effect on the expansion of the steam in the turbine and ultimately on the power output per unit mass of steam and hence the overall cycle efficiency.

1. Cycle Efficienies

1.2. Introduction

Early reciprocating steam engines and most steam locomotives were designed to operate on an open cycle where the exhaust steam was discharged to the atmosphere. This necessitated an adequate supply of fresh water.

Impurities in the water accumulated in the boiler during the steam generating process and some form of water treatment in the boiler or prior to the water entering the boiler was required. If however the exhaust steam was condensed and re-used the need for fresh supplies and for water conditioning was substantially reduced.

In addition a substantial benefit was obtained from the expansion of the steam down to vacuum conditions in a condenser leading to improved efficiency. This cycle of boiling, expansion, condensation and return to the boiler is commonly known as the Rankine Cycle.

Steam turbines generally operate within such a thermodynamic cycle with work produced by the expansion of steam from a high pressure to a low pressure. After condensation some work is required to pump the water back into the boiler.

The work required in pumping the liquid against the pressure difference is considerably less than the work produced by the steam in expanding across the same pressure difference.

The prime energy input to the cycle is that required to generate steam from water. Work is produced in the turbine and heat is rejected when the steam is condensed to water.

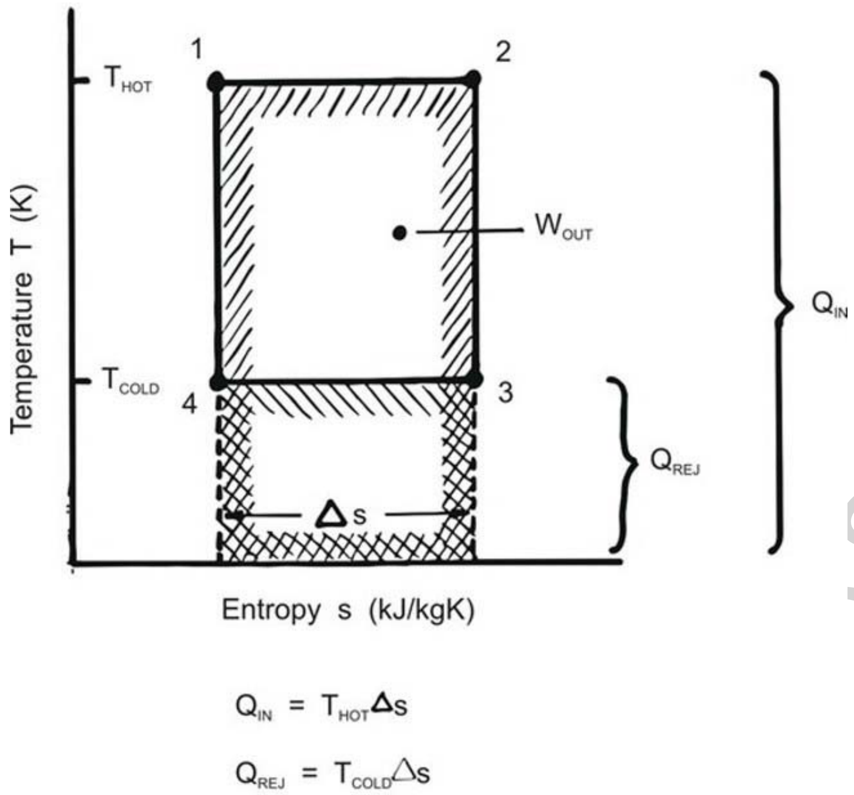

Figure 1: Carnot cycle

1.2. Carnot Cycle

The Carnot cycle is illustrated in Figure 1. In this cycle heat is added to the working fluid at a high temperature and rejected at a low temperature. The top temperature is limited by material properties and the bottom temperature by ambient conditions. The cycle is completed by isentropic (reversible adiabatic) processes between the two temperatures. This is an ideal situation but by using steam and water as the working fluid it is possible to approach this situation. By boiling water at a fixed elevated pressure, heat addition at a constant high temperature can be achieved. Similarly by condensing steam at a fixed reduced pressure (high vacuum conditions), heat rejection at a constant low temperature can be achieved. This low temperature is close to ambient conditions. Expansion of steam from high pressure to low pressure in a turbine in a reversible adiabatic manner that is without fluid friction or heat transfer is isentropic. Similarly compression of water is isentropic but the rise in temperature during compression is small and heat must be added to bring the temperature up to the point where steam begins to be generated. This process of heating the compressed water at temperatures below the top temperature is the only deviation from the ideal Carnot cycle and leads to a reduction in the theoretical efficiency for the cycle. This reduction in efficiency can be demonstrated with reference to Figure 2. For the Carnot cycle the total heat added Q_{in} is area ABEF while the work done W_{out} is area ABCD. For the water-steam cycle the total heat added Q_{in}^* is area HBEFG while the work done W_{out}^* is area HBCDG. The difference ΔW between the two cycles is area AGH. The Carnot cycle efficiency is as follows:

$$\eta_{Carnot} = W_{out} / Q_{in} \tag{1}$$

The water-steam cycle efficiency is given by:

$$\eta_{\text{water-steam}} = W^{*}_{\text{out}} / Q^{*}_{\text{in}} = (W_{\text{out}} - \Delta W)/(Q_{\text{in}} - \Delta W) \qquad (2)$$

Since W_{out} is always less than Q_{in} it is evident that $\eta_{\text{water-steam}}$ will always be less than η_{Carnot}. The ideal water-steam cycle described above may be used as a reference against which real water-steam cycles may be compared and is known as the Rankine Cycle.

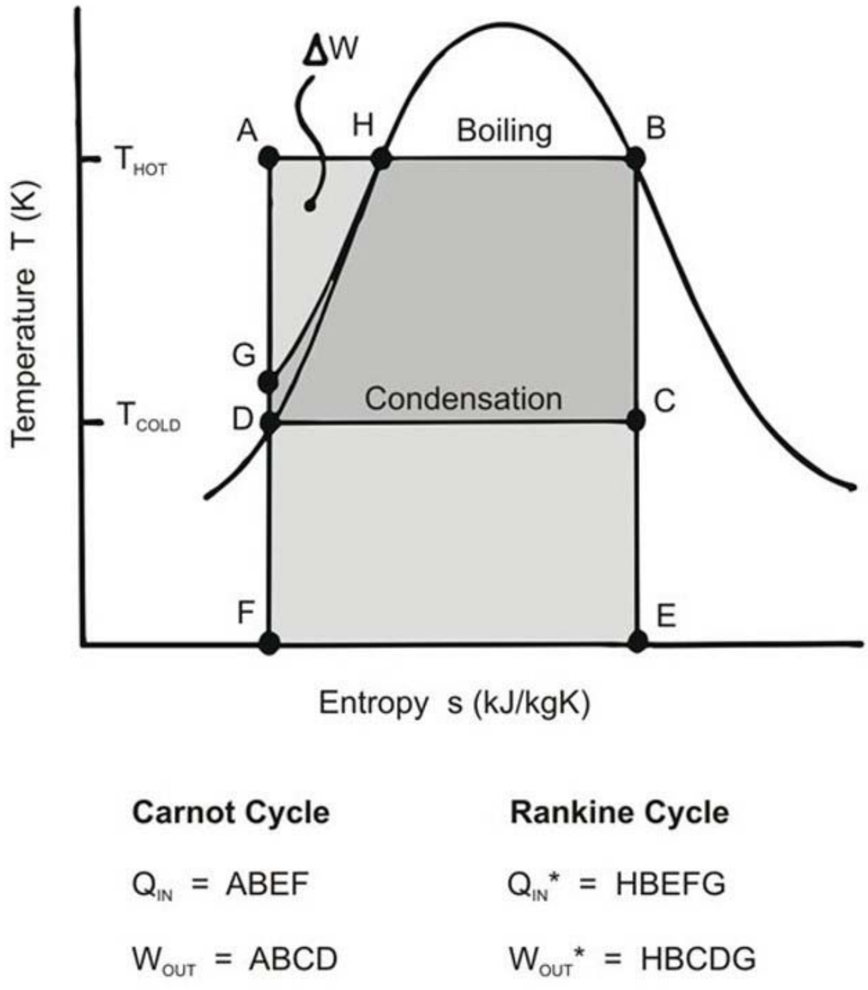

Figure 2: Comparison of Carnot cycle and Rankine cycle

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Biographical Sketch

Robin Chaplin obtained a B.Sc. and M.Sc. in mechanical engineering from University of Cape Town in 1965 and 1968 respectively. Between these two periods of study he spent two years gaining experience in the operation and maintenance of coal fired power plants in South Africa. He subsequently spent a further year gaining experience on research and prototype nuclear reactors in South Africa and the United Kingdom and obtained M.Sc. in nuclear engineering from Imperial College of London University in 1971. On returning and taking up a position in the head office of Eskom he spent some twelve years initially in project management and then as head of steam turbine specialists. During this period he was involved with the construction of Ruacana Hydro Power Station in Namibia and Koeberg Nuclear Power Station in South Africa being responsible for the underground mechanical equipment and civil structures and for the mechanical balance-of-plant equipment at the respective plants. Continuing his interests in power plant modeling and simulation he obtained a Ph.D. in mechanical engineering from Queen's University in Canada in 1986 and was subsequently appointed as Chair in Power Plant Engineering at the University of New Brunswick. Here he teaches thermodynamics and fluid mechanics and specialized courses in nuclear and power plant engineering in the Department of Chemical Engineering. An important function is involvement in the plant operator and shift supervisor training programs at Point Lepreau Nuclear Generating Station. This includes the development of material and the teaching of courses in both nuclear and non-nuclear aspects of the program.