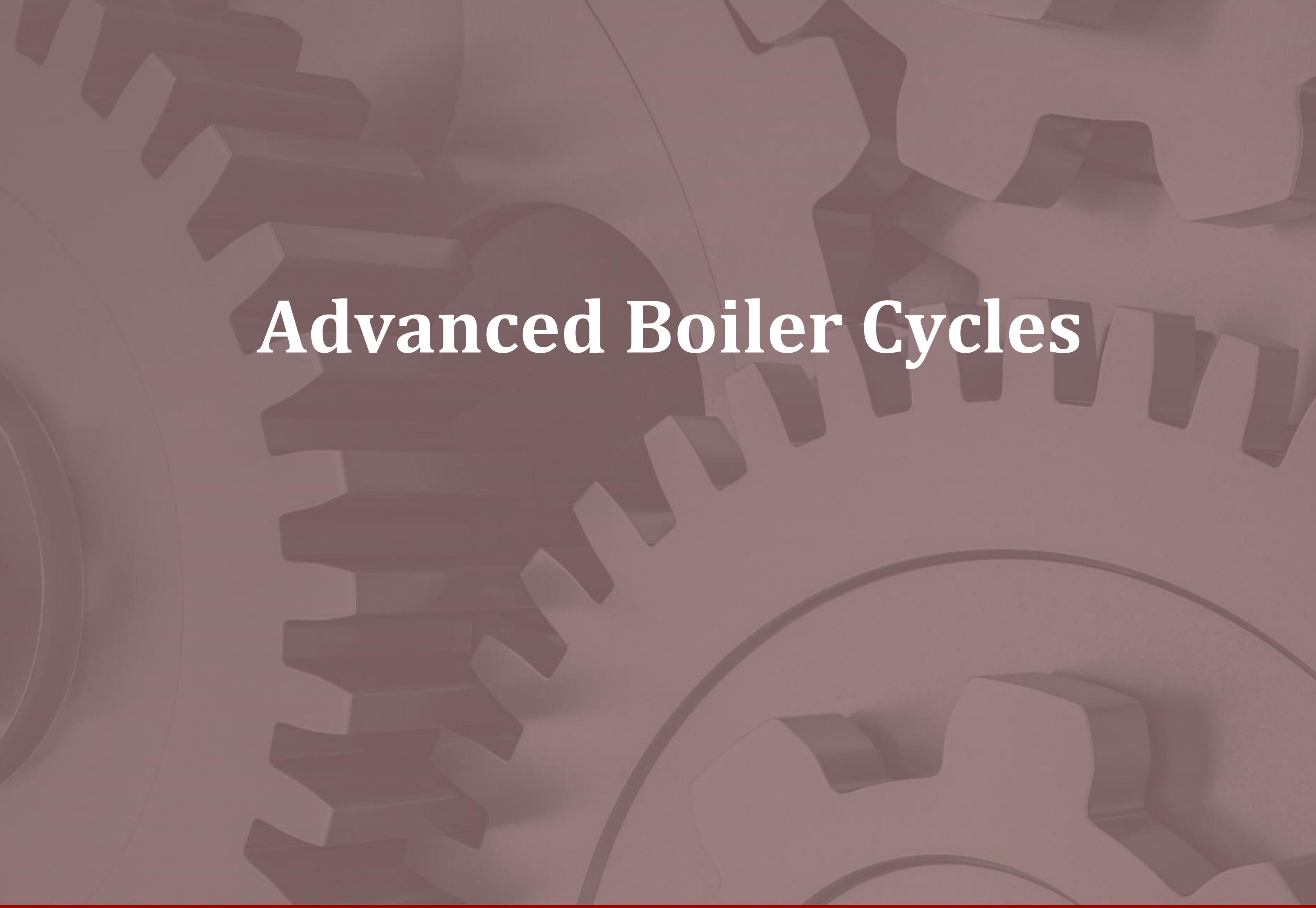

Advanced Boiler Cycles

An Online Continuing Education Course for Engineers

Course Number: M-1009

Credit: 1 Hour / 1 PDH / 1 CPD

Advanced Boiler Cycles

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Introduction

Supercritical phase of steam is reached when its pressure is raised above the critical point (3,208 psia). When in this phase, there is no physical delineation between the liquid and the vapor phases. Conventional drum-type boilers have no application at supercritical pressures. There is considerable increase in efficiency in cycles operating within this pressure and temperature range. There were several power plants built in the late 1950's and early 1960's that were designed to operate in the supercritical range. They earned reputations of high efficiencies, but low reliability and non-suitability for cycling operation. Their popularity and utilization, however, continued in Europe and Asia. Development in metallurgy and welding techniques overcame many of the early problems, and there is a resurgence of interest in supercritical technology in the United States.

Advanced Boiler Cycles

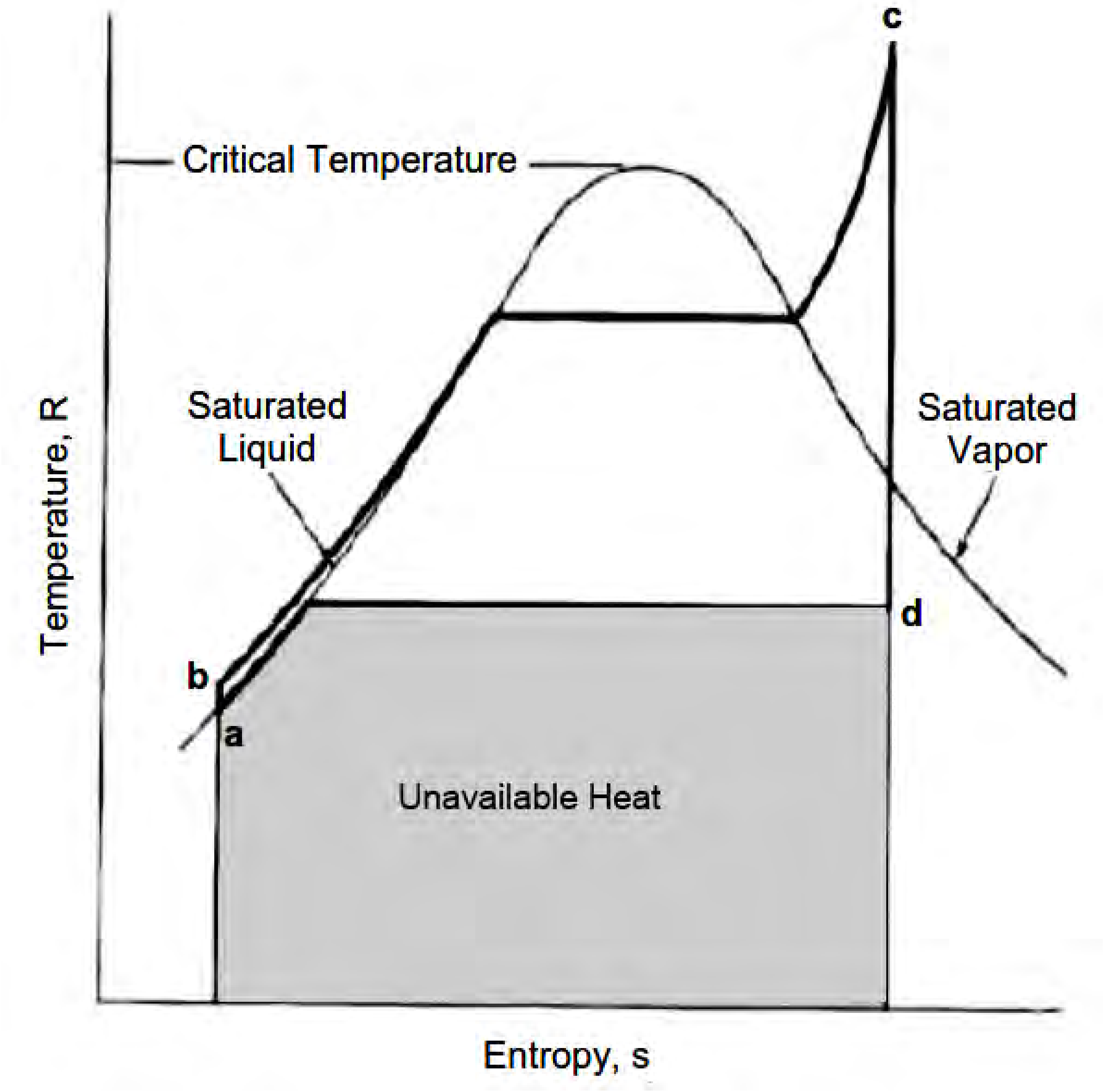
For studies involved in the variation of the basic steam cycle, it is necessary to thoroughly understand the properties of steam, the effects of pressure and temperature, and the use of superheat. A brief review of the fundamentals that apply to the generation of steam will be helpful.

The theoretical amount of work that can be obtained from steam used in a prime mover is equivalent to the change in its total heat content from its condition at the entering state to that at its exhaust state.

The vaporization of water occurs in two steps: First by adding heat to the water to raise it to boiling from the vapor / water interface, the continued addition of heat will cause the steam to become superheated. The superheated steam cannot condense as long as it is above the saturation temperature corresponding to the saturation pressure. In a drum-type boiler, this water / vapor interface is maintained in the steam drum. Once the saturated steam leaves the steam drum, it passes to the superheater tube banks where it is superheated.

Basic Ideal Rankine Cycle

The basic reversible Rankine superheat cycle plotted on Temperature / Entropy coordinates is illustrated below. This is the ideal cycle upon which drum type boilers are based.



Temperature-entropy diagram of the ideal Rankine cycle

The boiler feed pump raises the feedwater temperature isentropically from point a to point b. Next, heat is added in the boiler at constant pressure as the two- phase fluid circulates through the boiler generating tubes and steam drum. After the saturated steam leaves the drum, it enters the superheated phase, and the temperature rises to point c.

The area under the curve (the integral of Tds) represents heat. Heat is added from point a to point d, and is rejected from point d to point a. The shaded area represents heat rejected from the cycle in the condenser. The net work of the cycle, therefore, is represented by the area under a b c d minus the shaded area. The heat rejected is a function of the temperature of the heat sink, which nearly always is a large body of water or the atmosphere. The heat sink average temperature is generally about 60 deg. F. This fixes the heat rejected from a cycle as a function of a 60 deg. F. temperature. Therefore, to increase the net work, and thus the efficiency of a cycle, the area under the curve a b c d must be maximized.

Rankine Regenerative Cycle

A nearly universal variation to power plant Rankine cycles is the regeneration cycle. The Rankine regenerative cycle utilizes partially expanded steam extracted from the turbine at various points to heat the condensate and feedwater on its way back to the boiler or steam generator. The schematic of a regenerative cycle with two stages of feedwater heating is shown below. High pressure steam is extracted and directed to the high pressure feedwater heater # 1 (line 3). Low pressure steam is extracted at a lower pressure turbine stage and is directed to low pressure feedwater heater #2 (line 4). For simplicity, only two feedwater heating stages are shown here, however in large power plants as many as eight stages may be employed. Completely reversible heat transfer can take place only when there is no temperature difference between the heating and cooling media. This is physically impossible, of course, because a temperature difference is required for heat transfer to take place. Therefore, completely reversible heat transfer is impossible. (Heat can flow only from hot to cold).

However, as the temperature difference between hot and cold are closer, the increase in entropy is less, so the heat transfer is more efficient. This does not mean that the heat transfer is more **effective** when the temperature difference is less. The **rate** of heat transfer is proportional to the temperature difference between hot and cold, but the greater the temperature difference, the greater the increase in entropy during the process. What this means is that incremental steps of heat transfer to the feedwater increases the cycle efficiency over having all of the heat transfer taking place within the boiler.

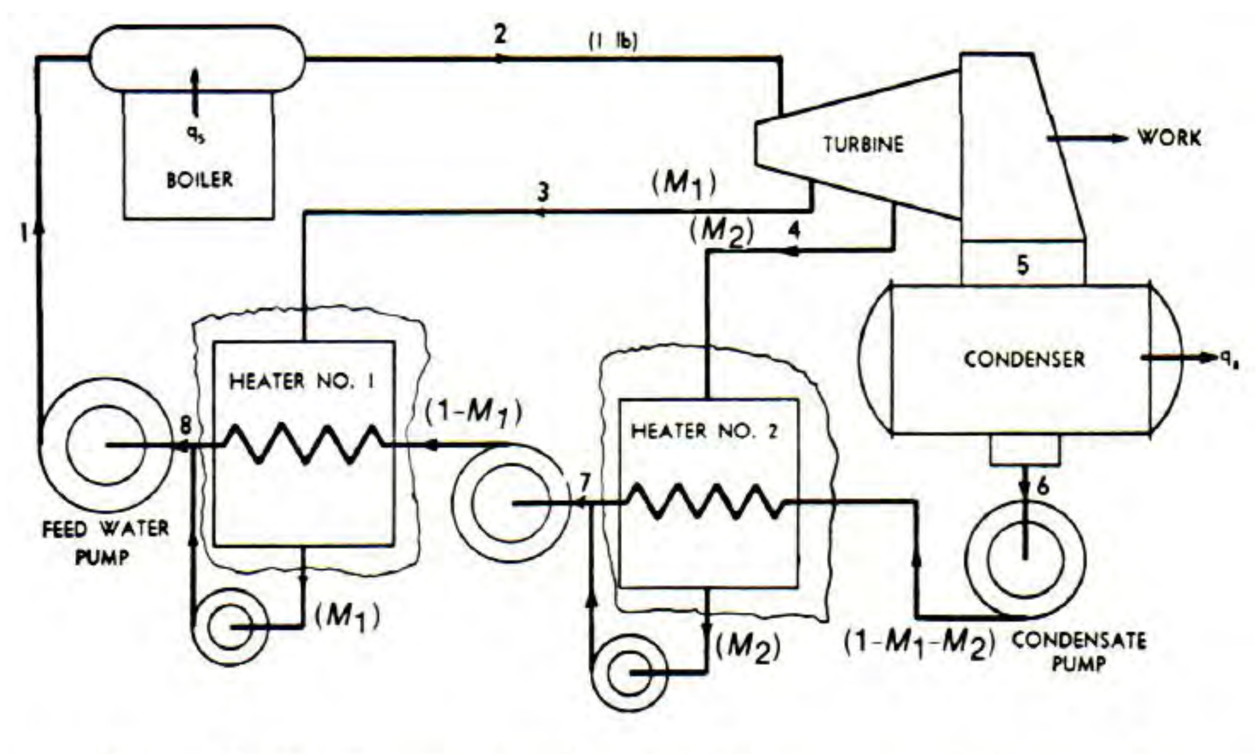


Figure 9–6. Apparatus for Rankine regenerative cycle.

The regenerative Rankine cycle is illustrated below. It can be shown that the best efficiency for a given number of heaters is realized when the temperature range per heater is approximately equal. Accordingly, for the cycle being illustrated for additional heaters, the same plan would be followed, solving temperature difference between the saturated vapor at the boiler pressure and the saturated liquid at the condenser is divided into three equal parts. The optimum extraction pressures are the saturation pressures corresponding to these saturation temperatures. The weight of steam to be removed at each extraction point is calculated by setting up a heat balance across each heater. Equating the total heat transferred from the extracted steam to heater #1 gives Q steam = Q feedwater.

h = enthalpy in BTU / lb. M = steam flow in lb / hr

$M_1 (h_3 - h_s) = (1 - M_1)(h_s - h_7)$

In a similar manner, a heat balance may be drawn across the second heater to give:
$M_2 (h_4 - h_7) = (1 - M_1 - M_2)(h_7 - h_6)$

By getting the enthalpies from the steam tables and solving for M_1, the result may be used to solve for M_2 . The thermal efficiency for the cycle would be:

$$\frac{(h_2 - h_1) - (1 - M_1 - M_2)(h_5 - h_6)}{h_2 - h_1}$$

For additional heaters, the same plan would be followed, solving for each weight in order.

The increase in efficiency must result in an operating cost reduction that is greater than the increased capital cost of the heaters and the additional piping. In a large power plant with today's fuel costs, this can economically justify eight stages of feedwater heating.

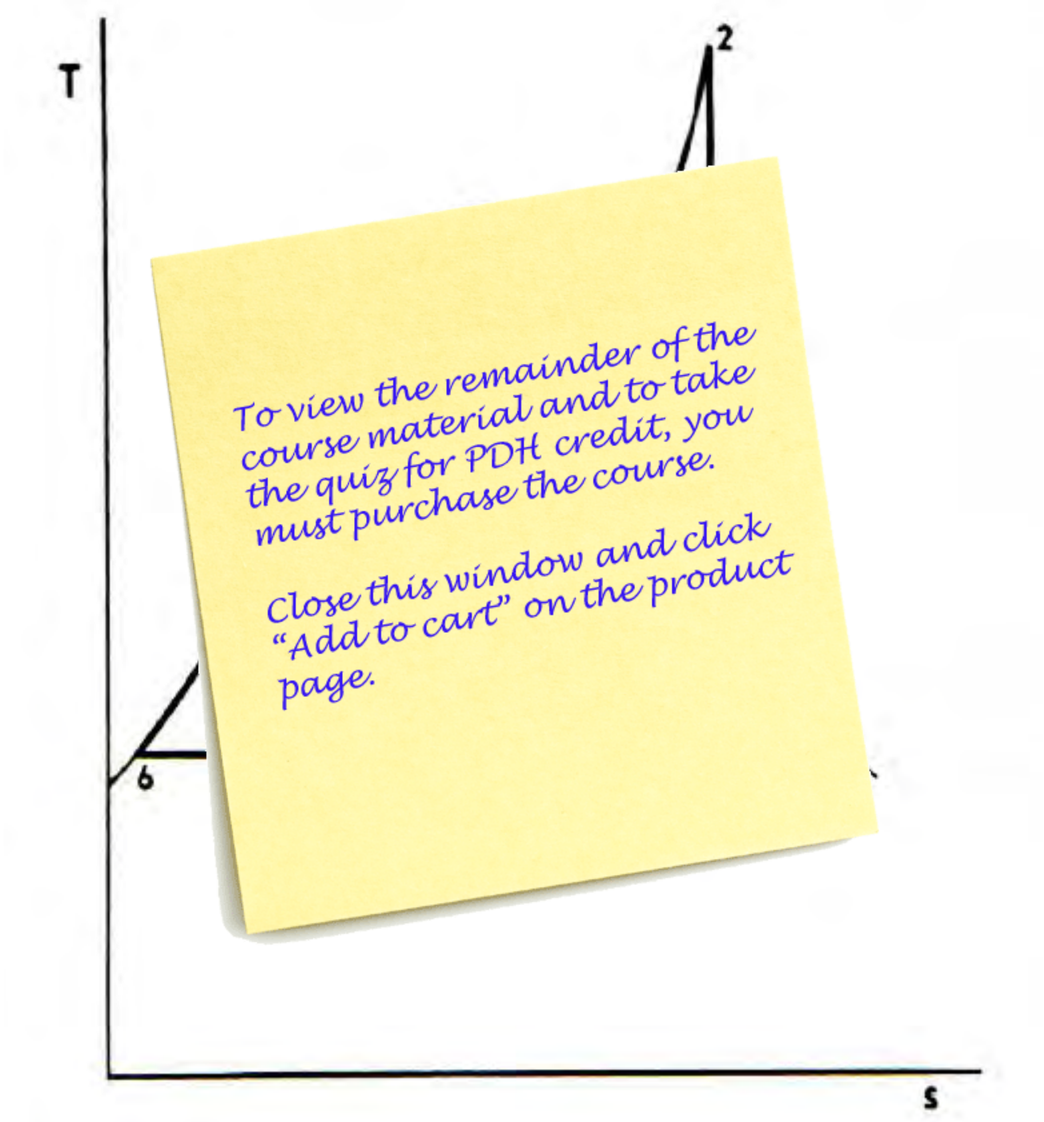


Diagram for Regenerative Rankine cycle

Reheat Cycle

Another common variation of the basic Rankine cycle is the Rankine reheat cycle. In order to take advantage of the additional heat added, as well as to gain the practical advantage of drier steam at the turbine exhaust, most power plants use the Rankine Reheat cycle, illustrated in the