6 CLASSICAL STEAM POWER CYCLES

6.1 CONVENTIONAL FLAME POWER CYCLES

6.1.1 BASIC HIRN OR RANKINE WITH SUPERHEATING CYCLE

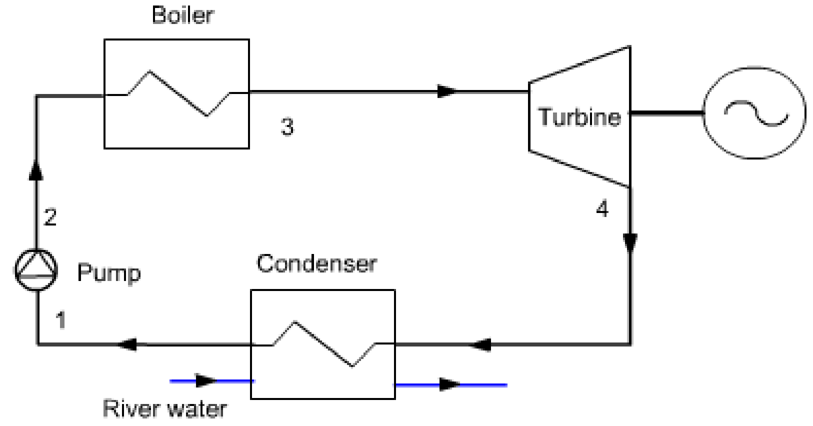

Figure 6.1.1: Sketch of a steam power plant

Hirn (or Rankine with superheating) cycle uses a condensable fluid, which is cooled at a temperature and pressure sufficient for it to be fully liquefied before compression. Under these conditions, the compression work is almost negligible compared to the expansion work (although it represents about 60% in a gas turbine). The compressed liquid is vaporized and superheated in the boiler by heat exchange with the hot source, then expanded and condensed. Fluid two-phase state during condensation and vaporization phases is very favorable for heat transfer.

The block diagram of a steam power plant operating on the ideal Hirn cycle is given in figure 6.1.1 (we return to the cycle studied as an example in section 6.1 of Part 2). The numerical values chosen here correspond to a conventional fossil-fired plant cycle, whose technologies will be discussed in section 6.2.

Such a plant includes four basic components: a pump, a boiler, a turbine and a condenser, through which passes the same water flow-rate.

For reasons stated in section 2.3.6 of Part 2, the pump and the turbine can be assumed adiabatic. As for the boiler and condenser, at first approximation we can make the assumption that they are isobaric.

6.1.1.1 Cycle description

At point 1, water is liquid, at a temperature of approximately 20 °C and at low pressure (0.023 bar). A pump pressurizes it to 165 bar (point 2), which represents a significant compression ratio (around 7000).

Compression (1-2) of the liquid can be legitimately considered isentropic and temperature T remains approximately constant. As the liquid isobars are virtually merged with the beginning of the vaporization curve (see section 2.6.6.1 of Part 2), point 2 is virtually identical with point 1 on the entropy diagram of Figure 6.1.2.

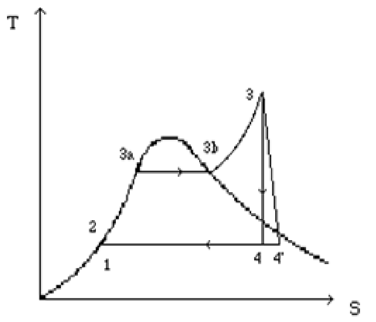

Figure 6.1.2: Steam cycle in an entropy chart

Pressurized water is then heated at high temperature in the boiler, heating comprising the following three steps, clearly visible in Figure 6.1.2:

- liquid water heating in the economizer from 20 °C to approximately 355 °C, dew point temperature at 165 bar: process (2-3a) in the entropic chart. Point 3a is on the vaporization curve at ordinate 355 °C on the same isobar as point 2;
- vaporization at constant temperature 355 °C in the vaporizer: process (3a-3b). Vaporization being carried out at constant pressure and temperature, it results in the chart in a horizontal segment 3a-3b. Point 3b is therefore on the descending branch of the vaporization curve, or dew point curve, at its intersection with the horizontal line of temperature 355 °C, still at the 165 bar pressure P_2;
- superheating from 355 °C to 560 °C in the superheater: process (3b-3). Point 3 is still assumed to be at the same pressure, but at temperature T_3 = 560 °C. It is thus at the intersection of isobar P = 165 bar and the horizontal of ordinate T = 560 °C.

Process (3-4) is an adiabatic expansion from 165 bar to 0,023 bar. In the ideal cycle, obtained without irreversibility and hence constant entropy, point 4 is at the intersection of the vertical passing through point 3 and isobar 0.023 bar. The point being in the mixed zone, the latter is confused with the horizontal T ≈ 20 °C. The quality here is x = 0.74. The real point 4' is at the same pressure as point 4, but its entropy is different because of irreversibilities (larger by the second law). Its enthalpy can be determined if one knows the turbine isentropic efficiency. Two cases may arise:

- either point 4' is in the mixed zone, and it is also on isotherm T ≈ 20 °C, closer to the dew point curve;
- or it is in the vapor zone, on isobar P = 0.023 bar, at T > 20 °C.

For example, with an isentropic efficiency of 0.85, the point at the end of expansion is 4', at the right of 4, and quality reaches the value of 0.84.

The liquid-vapor mixture is then condensed to liquid state in a condenser, heat exchanger between the cycle and the cold source, e.g. by water from a river. The cycle is thus closed.

6.1.1.2 Cycle modeling

The technical fluid (water) condensing, it is of course impossible to model it with the approximation of perfect or ideal gas, and thus to obtain simple analytical performance expressions for this plant.

6.1.6 SUPERCRITICAL CYCLES

As we shall see in the next section, the optimum technical and economic capacity of flame Hirn cycles until recent years matched with boiler conditions of about 560 °C and 165 bar, leading, with a reheat and without extraction, to a thermodynamic efficiency close to 40%. To significantly increase the efficiency, it is possible to use so-called supercritical cycles in which water pressure exceeds the critical pressure of 221.2 bar.

The result is obviously much higher stress for boiler tubes. Progress on the creep tube resistance can provide technological solutions unthinkable a short time ago. For example, the pipe thickness needed to withstand a pressure of 225 bar and a temperature of 600 °C changed from 250 mm with steel P22 at 2.25% Cr, to 93 mm with P91 steel with 9% Cr, and 68 mm with steel HCM12A at 12% Cr (Jayet-Gendrot & al, 1999).

Another constraint faced by supercritical boilers is the following: due to the absence of vaporizer, you cannot cool the furnace by pipe screens traversed by boiling water with very high heat transfer coefficients. This is why a different technology is used, without drum separator, in so-called mono-tubular boilers (improperly because in reality the layers of tubes are arranged in parallel), or in English "once-through" to indicate the absence of recirculation. These tubes are fluted with internal and external fins, mounted in spiral bundles.

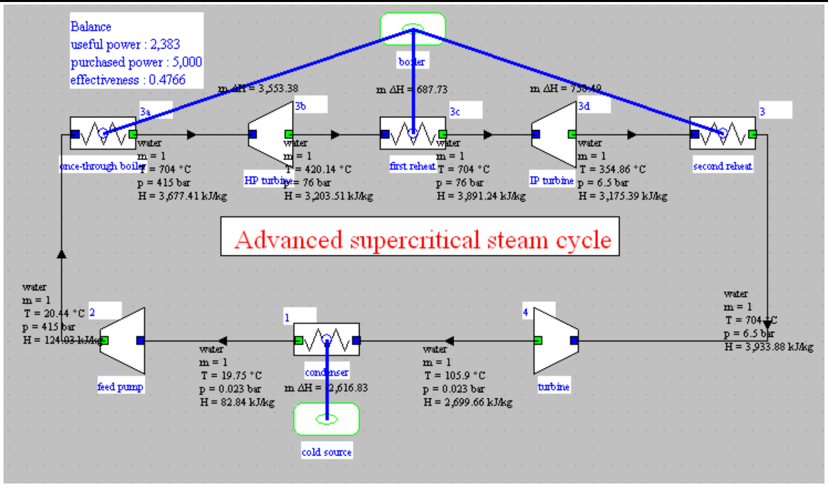

Figure 6.1.13: Synoptic view of a supercritical steam cycle

Supercritical cycles are not new (40% of former Soviet Union plants are supercritical, as well as more than 150 plants in the U.S.). The recent trend is to seek out increasingly high boiler conditions, and two reheats. To fix ideas, we modeled in Thermoptim such an advanced supercritical steam cycle (Example 6.1.3). The efficiency reaches 47.7% (against 40% for a conventional subcritical cycle). Figures 6.1.13 and 6.1.14 show the cycle synoptic view, and its plot in a (s, x_h) exergy chart.

In this example, we have simplified things by keeping an expansion isentropic efficiency of 0.85 for the different turbines. As the expansion takes entirely place in the dry zone, higher values could have legitimately been taken (see section 5.7.4).

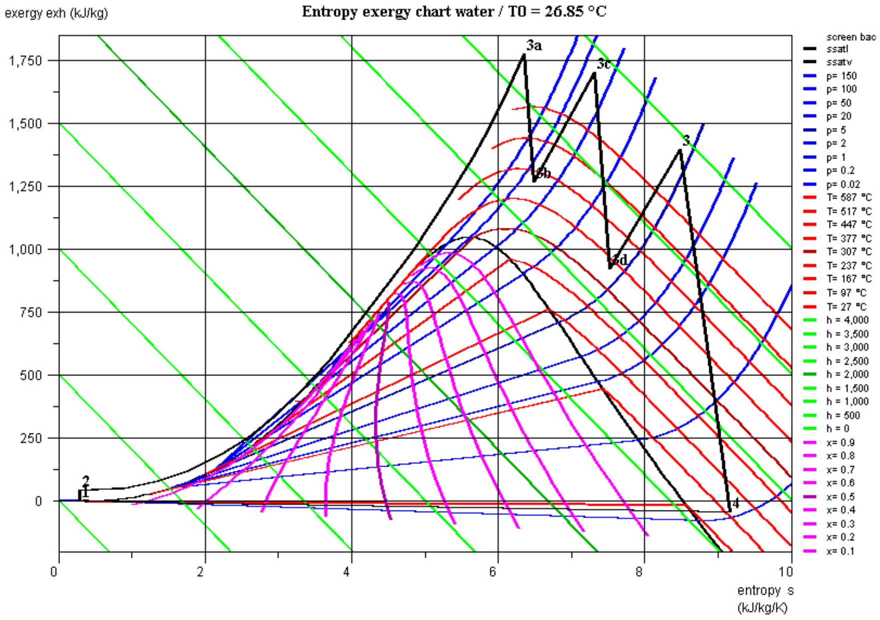

Figure 6.1.14: Supercritical steam cycle in the entropy-exergy chart

Thus, this technology provides efficiency gains between 6 and 10% depending on the steam pressure and temperature conditions, for a cost increased by 3 - 5%. As the addition of supercritical boilers offers more flexibility at the operational level than conventional drum boilers, their use is spreading more and more. Project Thermie 700 involving many EU manufacturers and utilities aims to achieve LHV efficiencies of 50%.