Thermodynamics

Chapter Two

The Simple Rankin Cycle

Dr. Mahmood Shaker
Department of Mechanical Engineering (2"nd" Stage)
College of Engineering– University of Basrah

Rankine Cycle

The Rankine cycle is an idealized thermodynamic cycle describing the process by which certain heat engines, such as steam turbines or reciprocating steam engines, allow mechanical work to be extracted from a fluid as it moves between a heat source and heat sink. The Rankine cycle is named after William John Macquorn Rankine, a Scottish polymath professor at Glasgow University.

Heat energy is supplied to the system via a boiler where the working fluid (typically water) is converted to a high-pressure gaseous state (steam) in order to turn a turbine. After passing over the turbine the fluid is allowed to condense back into a liquid state as waste heat energy is rejected before being returned to the boiler, completing the cycle. Friction losses throughout the system are often neglected for the purpose of simplifying calculations as such losses are usually much less significant than thermodynamic losses, especially in larger systems.

The Rankine cycle closely describes the process by which steam engines commonly found in thermal power generation plants harness the thermal energy of a fuel or other heat source to generate electricity. Possible heat sources include the combustion of fossil fuels such as coal, natural gas, or oil, renewable fuels like biomass or ethanol, nuclear fission, and concentrated solar power. Common heat sinks include ambient air above or around a facility and bodies of water such as rivers, ponds, and oceans. The ability of a Rankine engine to harness energy depends on the relative temperature difference between the heat source and heat sink. The greater the differential, the more mechanical power can be efficiently extracted out of heat energy, as per Carnot's theorem.

The efficiency of the Rankine cycle is limited by the high heat of vaporization of the working fluid. Unless the pressure and temperature reach supercritical levels in the boiler the temperature range, that the cycle can operate over, is quite small: Steam turbine entry temperatures are typically around 565 °C and condenser temperatures are around 30 °C. This gives a theoretical maximum Carnot efficiency for the turbine alone of about 63.8% compared with an actual overall thermal efficiency of less than 50% for typical power stations. This low steam turbine entry temperature (compared to a gas turbine) is why the Rankine (steam) cycle is often used as a bottoming cycle to recover otherwise rejected heat in combined-cycle gas turbine power stations.

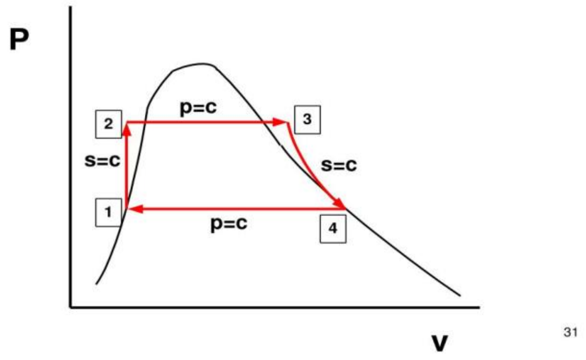
Rankine engines generally operate in a closed-loop where the working fluid is reused. The water vapor with condensed droplets often seen billowing from power stations is created by the cooling systems (not directly from the closed-loop Rankine power cycle). This 'exhaust' heat is represented by the "Qout" flowing out of the lower side of the cycle shown in the T– s diagram below. Cooling towers operate as large heat exchangers by absorbing the latent heat of vaporization of the working fluid and simultaneously evaporating cooling water to the atmosphere.

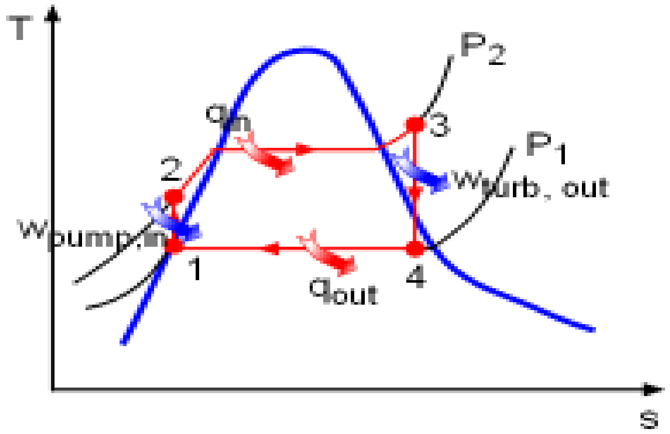
While many substances can be used as the working fluid, water is usually chosen for its simple chemistry, relative abundance, low cost, and thermodynamic properties. By condensing the working steam vapor to a liquid the pressure at the turbine outlet is lowered and the energy required by the feed pump consumes only 1% to 3% of the turbine output power and these factors contribute to higher efficiency for the cycle. The benefit of this is offset by the low temperatures of steam admitted to the turbine(s).

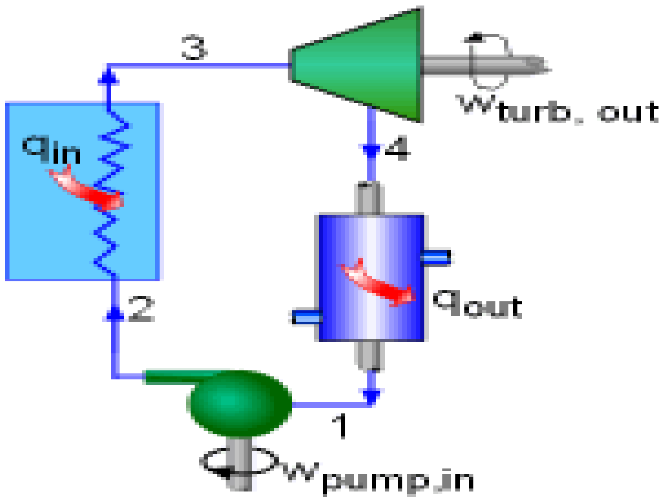
Gas turbines, for instance, have turbine entry temperatures approaching 1500 °C. However, the thermal efficiency of actual large steam power stations and large modern gas turbine stations are similar.

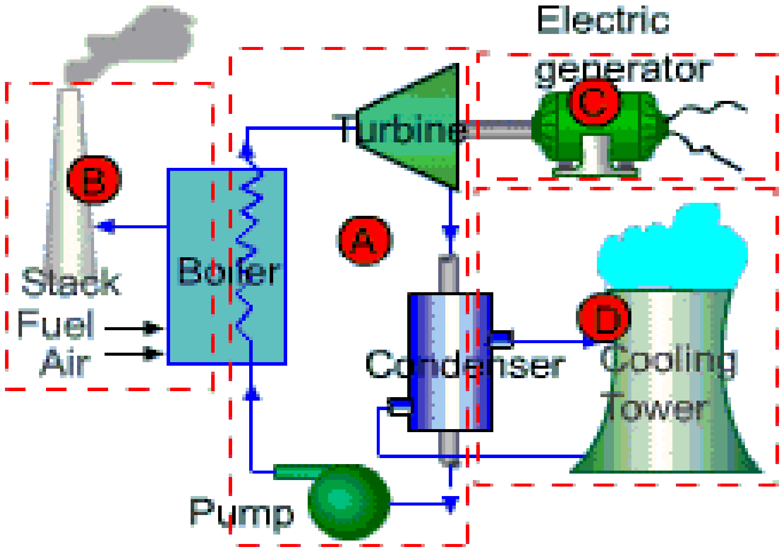
A slight modification upon Carnot Cycle will produce a more practical cycle, though of slightly lower thermal efficiency. This practical cycle is known as the Rankine cycle and is usually accepted as the ideal cycle for steam plants.

Ideal Rankine Cycle on a p-v diagram









Ideal Rankine cycle (Ideal Cycle for Vapour Power Cycle

Basic Cycle

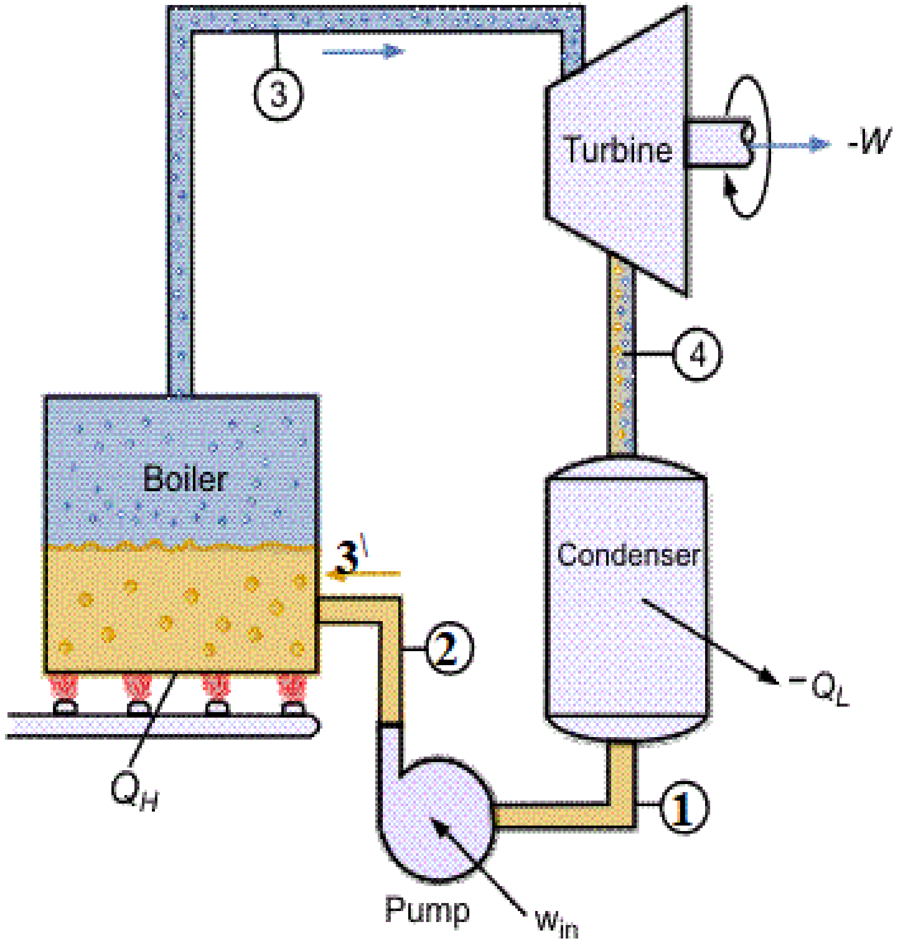
The Rankine cycle is the fundamental operating cycle of all power plants where an operating fluid is continuously evaporated and condensed. The selection of operating fluid depends mainly on the available temperature range. Figure shows the idealized Rankine cycle. The pressure-enthalpy (p – h) and temperature-entropy (T – S) diagrams of this cycle are given in Figure . The Rankine cycle operates in the following steps:

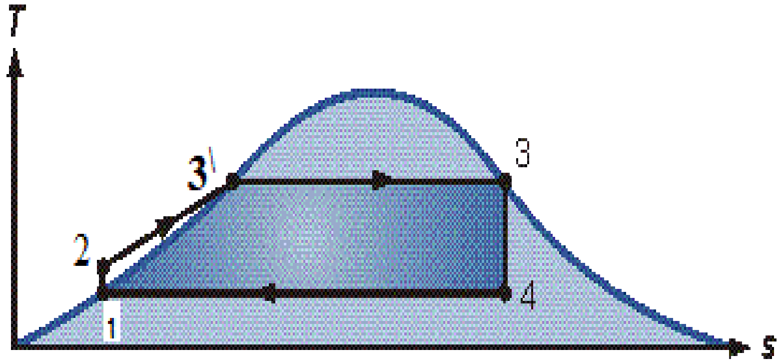
- Process 1 – 2 Isentropic Compression. The pressure of the condensate is raised in the feed pump. Because of the low specific volume of liquids, the pump work is relatively small and often neglected in thermodynamic calculations.

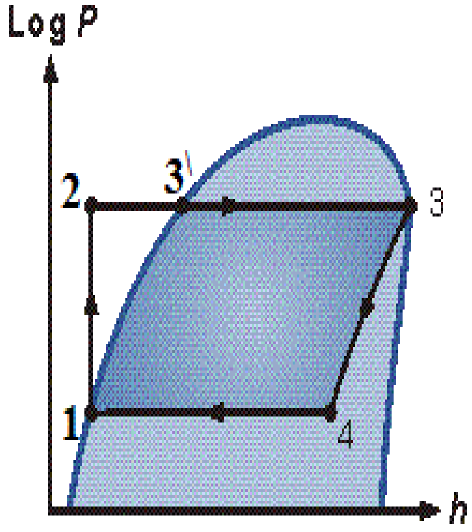
- Process 2 – 3 Isobaric Heat Transfer. High pressure liquid enters the boiler from the feed pump (2) and is heated to the saturation temperature ($3^{\backslash}$). Further addition of energy causes evaporation of the liquid until it is fully converted to saturated steam (3). where the high-pressure liquid is heated at constant pressure by an external heat source to become a dry saturated vapour. The input energy required can be easily calculated graphically, using an enthalpy–entropy chart (h–s chart, or Mollier diagram), or numerically, using steam tables or software. In other words, Process 2-3 is [Constant pressure heat addition in boiler]

- Process 3 – 4 Isentropic Expansion. The vapor is expanded in the turbine, thus producing work which may be converted to electricity. In practice, the expansion is limited by the temperature of the cooling medium and by the erosion of the turbine blades by liquid entrainment in the vapor stream as the process moves further into the two-phase region. Exit vapor qualities should be greater than 90%.

✹ Process 4 – 1 Isobaric Heat Rejection. The vapor-liquid mixture leaving the turbine (4) is condensed at low pressure, usually in a surface condenser using cooling water. The wet vapour enters a condenser, where it is condensed at a constant pressure to become a saturated liquid. In other words, Process 4-1 is [Constant pressure heat rejection in condenser].







In engineering analysis, the performance was achieved under idealized circumstances for the same inlet and exit states. Although there exits heat transfer between the device and its surroundings, most steady-flow devices are intended to operate under adiabatic conditions. Hence, normally an isentropic process is chosen to serve as the idealized process.

If the inlet is denoted by subscript 1 and exit is denoted by subscript 2, the energy balance for a one-inlet-one-exit control volume is

$$\dot{Q} - \dot{W} = \dot{m}\left((h_2 - h_1) + \left(\frac{v_2^2 - v_1^2}{2} \right) + g(z_2 - z_1) \right)$$

To simplify the calculations, neglect the change in potential energy and the change in kinetic energy across the cycle.

Pump (process 1-2): Pump pressurized the liquid water from the condenser prior to going back to the boiler. Assuming no heat transfer with the surroundings, the energy balance in the pump is

$$\mathbf{w_{pump,\,in} = h_2 - h_1}$$

$$\mathbf{h = u + pv}$$

$$\mathbf{w_{pump,\,in} = (u_2 + p_2v_2) - (u_1 + p_1v_1)}$$

$$\mathbf{w_{pump,\,in} = (p_2v_2 - p_1v_1) + (u_2 - u_1)}$$

$$\mathbf{w_{pump,\,in} = (p_2v_2 - p_1v_1) + (C_v T_2 - C_v T_1)}$$

When the water flow through the pump, there is no change in temperature and specific volume. i. e. $v_1 = v_2$, and $T_1 = T_2$

Thus the specific work is

$$w_{pump,\ in} = v\,(p_2 - p_1)\text{ , and the Total work } W_{pump,\ in} = V\,(p_2 - p_1)$$

Boiler (process 2-3): Liquid water enters the boiler and is heated to superheated state in the boiler. The energy balance in the boiler is

$$q_{in} = h_3 - h_2$$

Turbine (process 3-4): Steam from the boiler, which has an elevated temperature and pressure, expands through the turbine to produce work and then is discharged to the condenser with relatively low pressure. Neglecting heat transfer with the surroundings, the energy balance in the turbine is

$$w_{turbine,\ out} = h_3 - h_4$$

Condenser (process 4-1): Steam from the turbine is condensed to liquid water in the condenser. The energy balance in the condenser is

$$q_{out} = h_4 - h_1$$

For the whole cycle, the energy balance can be obtained by summarizing the four energy equations above. It yields,

$$(q_{in} - q_{out}) - (w_{turbine,\ out} - w_{pump,\ in}) = 0$$

The thermal efficiency of the Rankine cycle is determined from

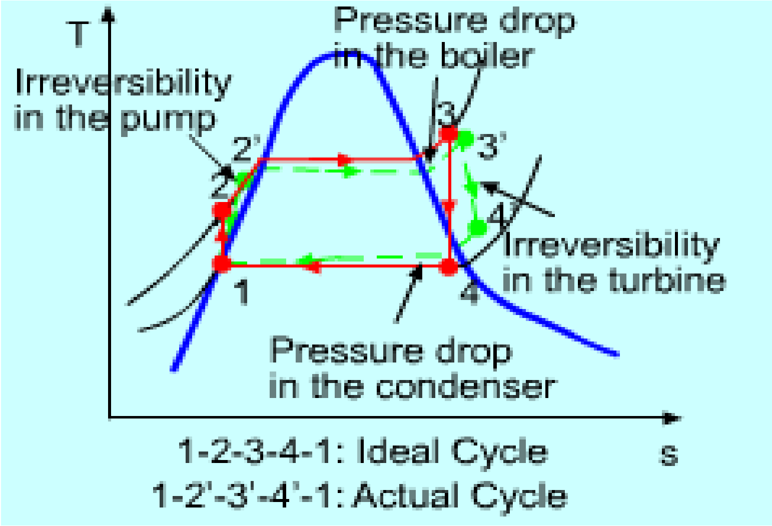
$$\eta_{ther.Rankin} = \frac{W_{net.out}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

where the net work output from the cycle is:

$$w_{net,out} = w_{turbine,\ out} - w_{pump,\ in}$$

Real Rankine cycle (non-ideal)

In a real power-plant cycle (the name "Rankine" cycle is used only for the ideal cycle), the compression by the pump and the expansion in the turbine are not isentropic. In other words, these processes are non-reversible (irreversible), and entropy is increased during the two processes. This somewhat increases the power required by the pump and decreases the power generated by the turbine.

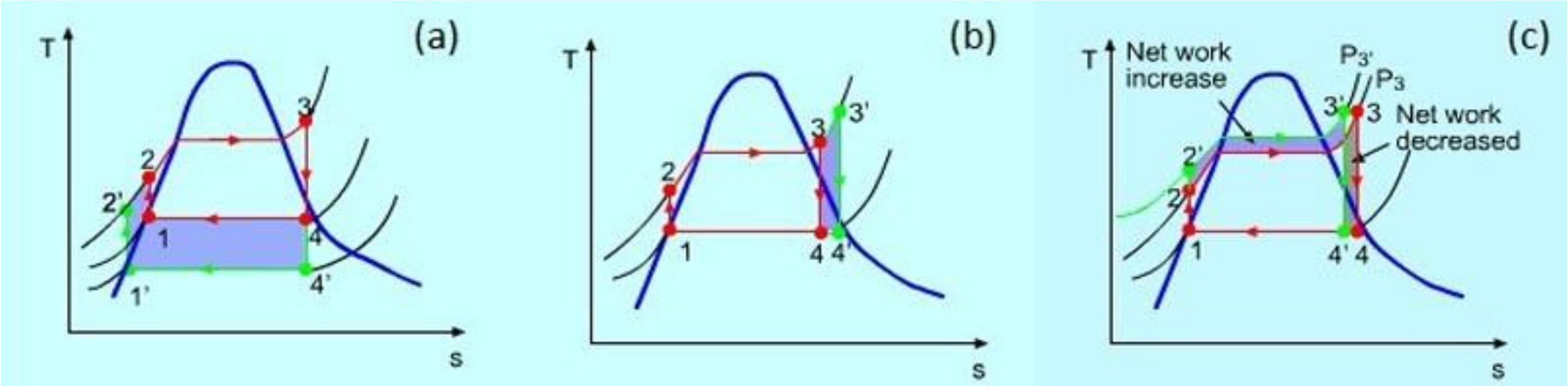


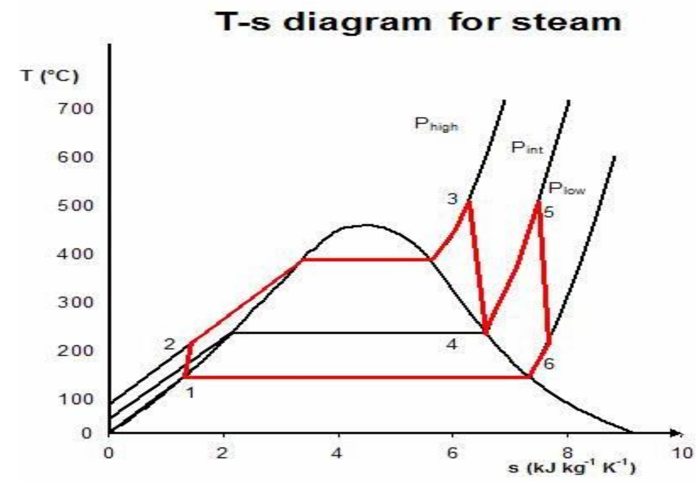
Enhancements of, and Effect of Design Parameters on, Rankine Cycles

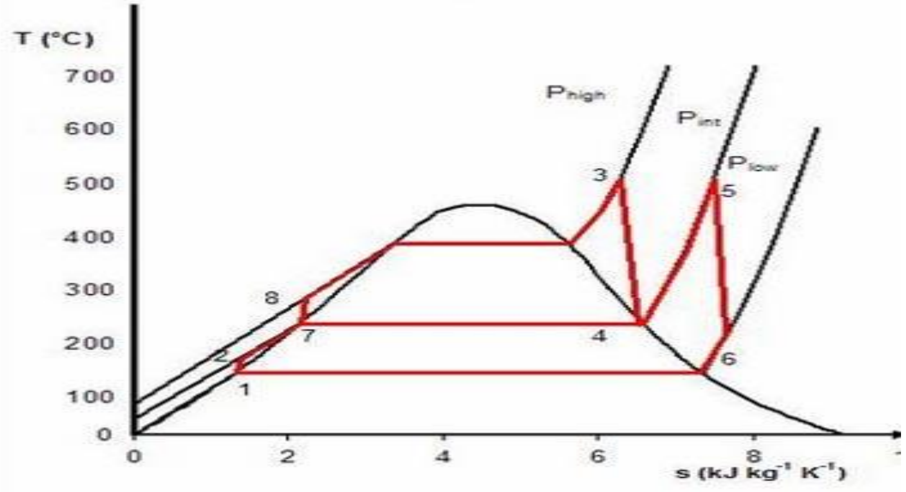
The basic Rankine cycle can be enhanced by several methods to increases the net work of the cycle. There are several scenarios of employment of the Rankine steam cycle in power plants, including solar plants. Those scenarios intend to increase the overall efficiency of the system. There are many ways to increase the efficiency of the basic Rankine cycle:

1. **Decreasing condenser pressure**. This results in a lower heat rejection temperature of the fluid in the condenser (pushing point 4 on the diagram in Fig. a downward), thus allowing the system to produce a greater network.
2. **Increasing the boiler pressure** results in a higher average steam temperature in the boiler. This effect allows additional work to be done in phases 2-3 (Fig. c). However, there is some loss of useful work in phases 3-4 because of the necessity to re-heat the steam. Reheating is used to mitigate the higher moisture content of the high-pressure steam.
3. **Superheating steam** to a higher temperature allows achieving a higher temperature differential, thus increasing the amount of work done by the cycle (Fig. b).
4. **Reheating**, . reheat removes the moisture and increases steam temperature after a partial expansion. reheat allows delivering more of the heat at a temperature close to the peak of the cycle. This requires the addition of another type of heat exchanger called a reheater. The use of the reheater involves splitting the turbine, i.e. use of a multistage turbine with a reheater. It was observed that more than two stages of reheating are unnecessary since the next stage increases the cycle efficiency only half as much as the preceding stage.

5. Regeneration, The regenerative Rankine cycle is so named because after emerging from the condenser (possibly as a subcooled liquid) the working fluid is heated by steam tapped from the hot portion of the cycle. On the diagram shown, the fluid at 2 is mixed with the fluid at 4 (both at the same pressure) to end up with the saturated liquid at 7. This is called "direct-contact heating". The Regenerative Rankine cycle (with minor variants) is commonly used in real power stations.







Superheating

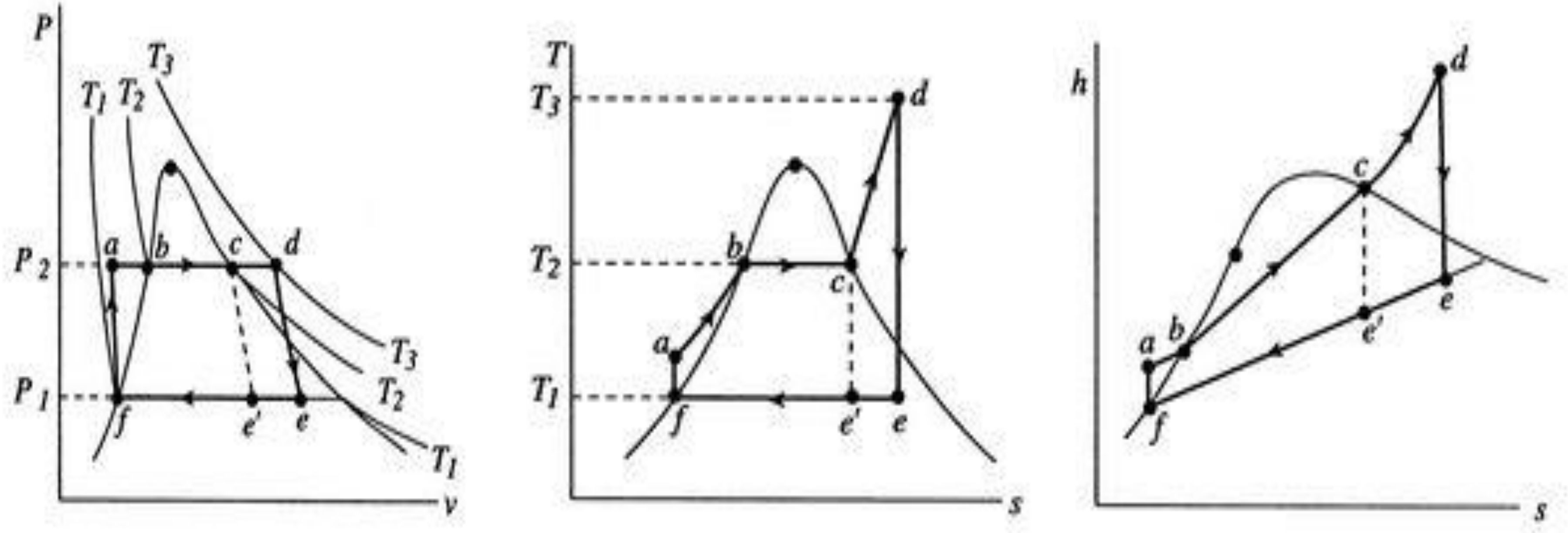
Increases the steam temperature above the saturation temperature, in other word, superheated vapour or superheated steam is a vapor at a temperature higher than its boiling point at the absolute pressure where the temperature is measured.

In particular, the efficiency of the steam turbine will be limited by water-droplet formation. As the water condenses, water droplets hit the turbine blades at high speed, causing pitting and erosion, gradually decreasing the life of turbine blades and efficiency of the turbine. The easiest way to overcome this problem is by superheating the steam. On the T– s diagram above, state 3 is at a border of the two-phase region of steam and water, so after expansion the steam will be very wet. By superheating, state 3 will move to the right (and up) in the diagram and hence produce a drier steam after expansion.

Diagrams for a Rankine cycle with superheating are given in Figure. The heat addition is continued past the point of vapor saturation, in other words the vapor is heated so that its temperature is higher than the saturation temperature associated with P_a $(= P_b = P_c = P_d)$

This does several things.

- First, it increases the mean temperature at which heat is added, , thus increasing the efficiency of the cycle.
- Second is that the quality of the two-phase mixture during the expansion is higher with superheating, so that there is less moisture content in the mixture as it flows through the turbine. (The moisture content at e is less than that at $e^{\backslash}$) This is an advantage in terms of decreasing the mechanical deterioration of the blading.



Rankine cycle with superheating