Lecture One
Steam Power Plants

Steam power plants operate on the principles derived from the first and second laws of thermodynamics. The thermodynamic power cycle that is the basic concept of steam power plants is called Rankine cycle. In a simple Rankine cycle; water is heated, turns into steam and spins a steam turbine which drives an electrical generator. After it passes through the turbine, the steam is condensed in a condenser and recycled to where it was heated.

Rankine Cycle

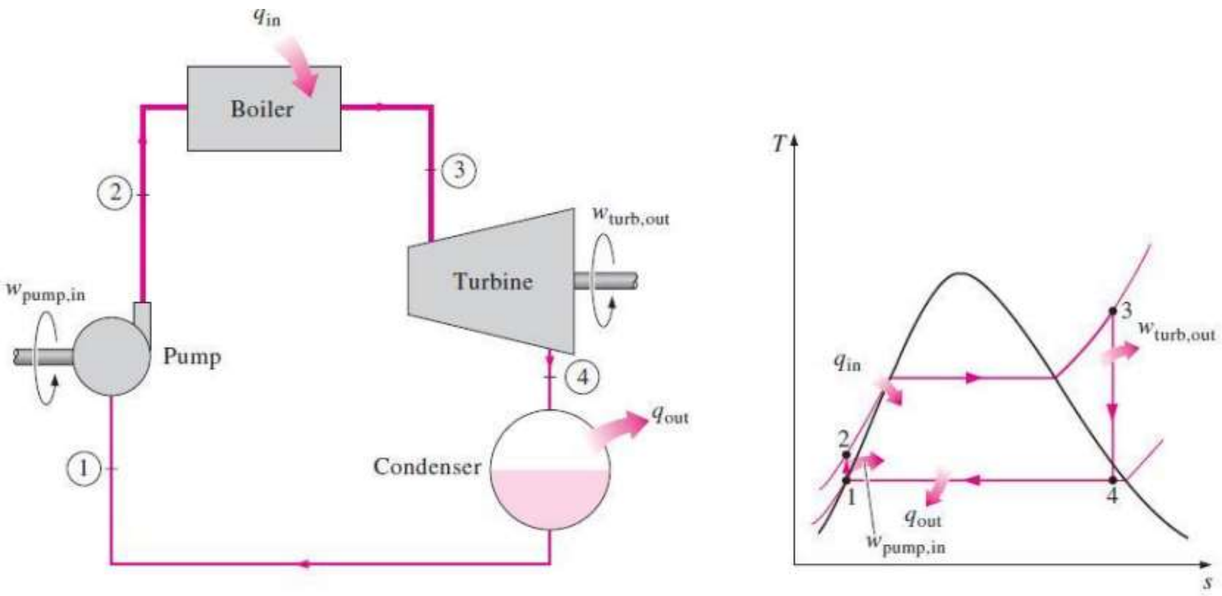
A schematic diagram of a steam power plant and a (T-S) diagram of a simple ideal Rankine cycle are shown in figure below. The ideal Rankine cycle does not involve any internal irreversibility and consists of the following four processes:

Process (1-2), isentropic compression in a pump: water enters the pump at state 1 as saturated liquid and is compressed isentropically to the operating pressure of the boiler. The water temperature increases somewhat during this isentropic compression process.

Process (2-3), constant pressure heat addition in a boiler: water enters the boiler as compressed liquid at state 2 and leaves as superheated vapor at state 3. The boiler is basically a large heat exchanger where the heat originating from a heat source is transferred to the water at constant pressure. The boiler, together with the section where the steam is superheated (the superheater), is often called the steam generator.

Process (3-4), isentropic expansion in a turbine: the superheated vapor at state 3 enters the turbine, where it expands isentropically and produces work by rotating the connected shaft. The pressure and temperature of steam drop during this process to the values at state 4, where steam enters the condenser. At this state, steam is usually a saturated liquid–vapor mixture with high quality.

Process (4-1), constant pressure heat rejection in a condenser: at state 4, steam is condensed at constant pressure in the condenser by rejecting heat to a cooling medium. Steam leaves the condenser as saturated liquid at state 1 and enters the pump completing the cycle.



Simple Ideal Rankine Cycle

The area under the process curve on a (T-S) diagram represents the heat transfer for internally reversible processes, it can be seen that the area under the process curve (2-3) represents the heat transferred to the water in the boiler and the area under the process curve (4-1) represents the heat rejected in the condenser. The difference between these two (the area enclosed by the cycle) is the network produced during the cycle.

Energy Analysis of the Cycle

All four components associated with the Rankine cycle (pump, boiler, turbine, and condenser) are steady-flow devices, and thus all four processes that make up the Rankine cycle can be analyzed as steady-flow processes. The kinetic and potential energy changes of the steam are usually small relative to the work and heat transfer terms and are therefore usually neglected. Then the steady-flow energy equation per unit mass of steam can be expressed as follows:

$$(q_{in} - q_{out}) + (w_{pump} - w_{turbine}) = h_e - h_i$$

- **For pump:** $q = 0$ **and** $w_{pump} = h_2 - h1$ or $w_{pump} = v\,(P_2 - P_1)$

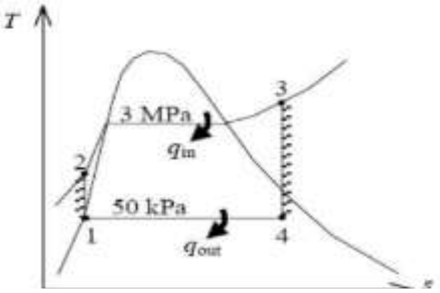
Where: $h_1 = h_f$ **and** $v = v_1 = v_f$ at P_1

- **For boiler:** $w = 0$ **and** $q_{in} = h_3 - h_2$
- **For turbine:** $q = 0$ **and** $w_{turbine} = h_3 - h_4$
- **For condenser:** $w = 0$ **and** $q_{out} = h_4 - h_1$

$$w_{net} = w_{turbine} - w_{pump} = q_{in} - q_{out}$$

$$\eta_{th} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

Example (5.1): A steam power plant operates on a simple ideal Rankine cycle between the pressure limits of 3 MPa and 50 kPa. The temperature of the steam at the turbine inlet is 300°C, and the mass flow rate of steam through the cycle is 35 kg/s. Show the cycle on a (T-S) diagram with respect to the saturation lines, and determine: (a) the thermal efficiency of the cycle (b) the net power output of the power plant.



Solution:

$h_1 = h_f = 340.54$ kJ/kg at $P1 = 50$ kPa

$v = v_1 = v_f = 0.00103\ \text{m}^3/\text{kg}$ at $P1 = 50$ kPa

$w_{pump} = v\,(P_2 - P_1) = 0.00103 \times (3000 - 50) = 3.04$ kJ/kg

$w_{pump} = h_2 - h1$

$\rightarrow h_2 = h_1 + w_{pump} = 340.54 + 3.04 = 343.58$ kJ/kg

At $P_3 = 3$ MPa and $T3 = 300°C$

$\rightarrow h_3 = 2994.3$ kJ/kg and $s_3 = 6.5412$ kJ/kg. K

At $P_4 = 50$ kPa and $s_4 = s_3$

$\rightarrow x_4 = s_4 - s_f\ sfg = 6.5412 - 1.0912\ 6.5019 = 0.8382$

$h_4 = h_f + x_4\, h_{fg} = 340.54 + 0.8382 \times 2304.7 = 2272$ kJ/kg

$q_{in} = h_3 - h_2 = 2994.3 - 343.58 = 2650.6$ kJ/kg

$q_{out} = h_4 - h_1 = 2272.3 - 340.54 = 1931.8$ kJ/kg

$w_{net} = q_{in} - q_{out} = 2650.6 - 1931.8 = 718.9$ kJ/kg

$$\eta_{th} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{1931.8}{2650.7}$$

$\boldsymbol{\eta th} = \mathbf{27.1}\%$ Ans.

$Power = m^{\circ} \times w_{net} = 35 \times 718.9$

$\boldsymbol{Power} = \mathbf{25.2\ kW}$ Ans.