Steam Power Plants

RANKINE CYCLE

Rankine cycle is a thermodynamic cycle derived from Carnot vapour power cycle for overcoming its limitations.

In earlier discussion it has been explained that Carnot cycle cannot be used in practice due to certain limitations.

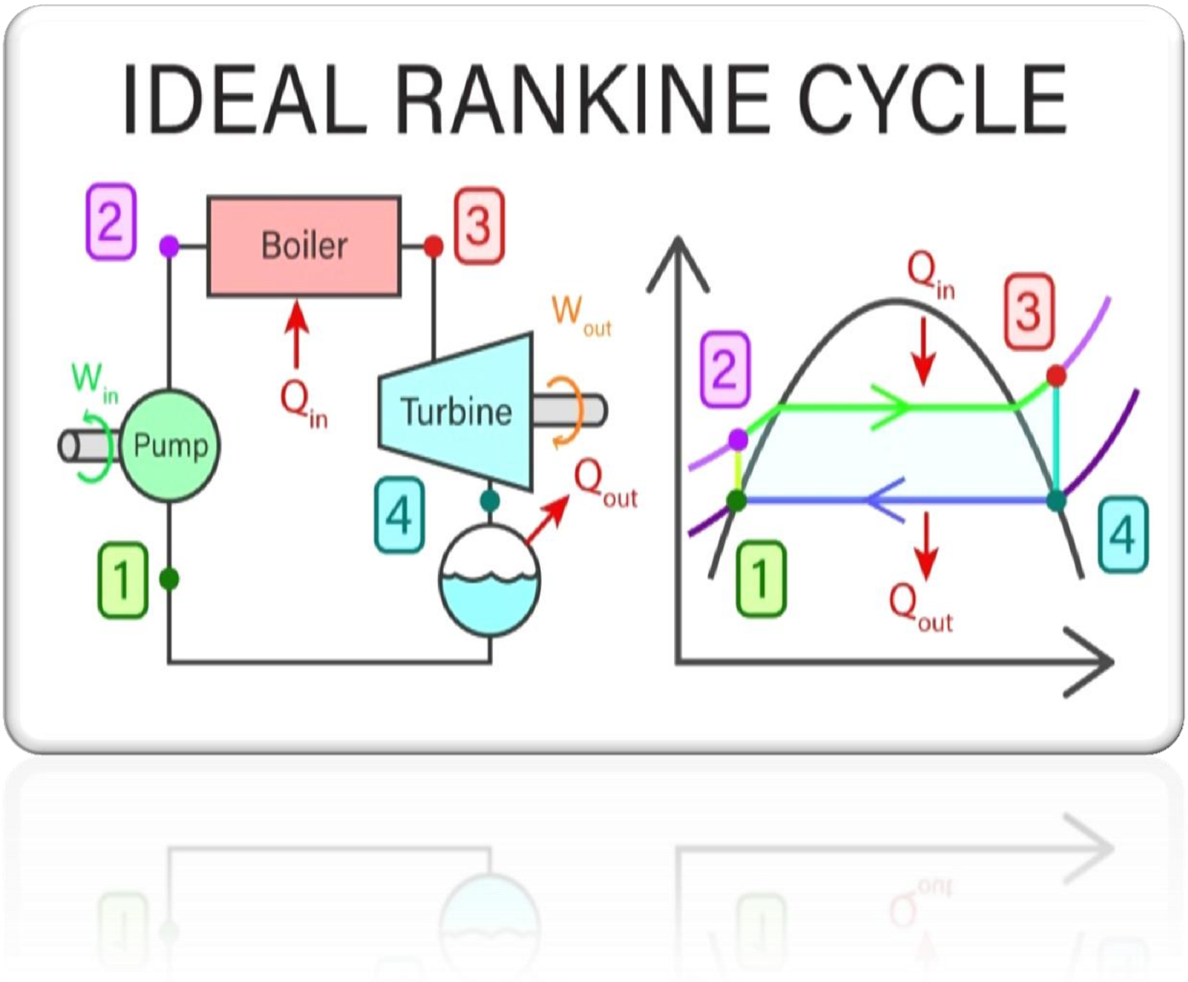
Rankine cycle has the following thermodynamic processes.

1 – 2 = Adiabatic pumping (in pump)

2 – 3 = Isobaric heat addition (in boiler)

3 – 4 = Adiabatic expansion (in turbine)

4 – 1 = Isobaric heat release (in condenser)



Let us understand the arrangement.

1 – 2: Condensate available as saturated liquid at state 1 is sent to feed pump for being pumped back to boiler at state 2. For unit mass, Pump work Wpump = h1 – h2.

Here pumping process is assumed to be adiabatic for the sake of analysis whereas it is not exactly adiabatic in the pump. From first and second law combined together; dh = T · ds + v · dp. Here in this adiabatic pumping process. ds = 0 Therefore dh = v · dp.

or (h1 – h2) = v1 (p1– p2)

or (h1 – h2) = v1 (p1 – p3). Where {as $p_2 = p_3$}

$W_{pump} = v_1(p_1 - p_3)$

2 – 3: High pressure water supplied by feed pump is heated and transformed into steam with or without superheat as per requirement. This high pressure and temperature steam is sent for expansion in steam turbine. Heat added in boiler, for unit mass of steam.

Qadd = (h3 – h2)

3 – 4: Steam available from boiler is sent to steam turbine, where it's adiabatic expansion takes place and positive work is available. Expanded steam is generally found to lie in wet region. Expansion of steam is carried out to the extent of wet steam having dryness fraction above 85% so as to avoid condensation of steam on turbine blades and subsequently the droplet formation which may hit hard on blade with large force. Turbine work, for unit mass, Wturbine = (h3 – h4).

4 – 1: Heat rejection process occurs in condenser at constant pressure causing expanded steam to get condensed into saturated liquid at state 4. Heat rejected in condenser for unit mass, Qrejected = (h4 – h1)

Rankine cycle efficiency can be mathematically given by the ratio of net work to heat added.

$$\eta_{Rankine} = \frac{W_{net}}{Q_{add}}$$

$$W_{net} = W_{turbine} + W_{pump}$$

$$W_{net} = (h_3 - h_4) + (h_1 - h_2)$$

$$\eta_{Rankine} = \frac{(h_3 - h_4) + (h_1 - h_2)}{h_3 - h_2}$$

$$\eta_{Rankine} = \frac{(h_3 - h_2) - (h_4 - h_1)}{h_3 - h_2}$$

$$\eta_{Rankine} = 1 - \frac{(h_4 - h_1)}{h_3 - h_2}$$

Where

$$W_{net} = Q_{add} - Q_{reject}$$

Bwr= $\frac{W_{pump}}{W_{turbine}}$

Work ratio= $\frac{W_{net}}{W_{turbine}}$

Energy Analysis of the Ideal Rankine Cycle

All four components associated with the Rankine cycle (the 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.

the *steady-flow energy equation* per unit mass of steam reduces to

$$(q_{in} - q_{out}) - (w) = h_e - h_I \qquad (\text{kJ/kg})$$

The boiler and the condenser do not involve any work, and the pump and the turbine are assumed to be isentropic.

the conservation of energy relation for each device can be expressed as follows:
Pump ($q = 0$): $w_{pump,in} = h_1 - h_2$
or,

$$w_{pump,in} = v(P_1 - P_2)$$

where

$$h_1 = h_{f@P_1} \text{ and } v \cong v_1 = v_{f@P_1}$$

Boiler ($w = 0$): $q_{in} = h_3 - h_2$

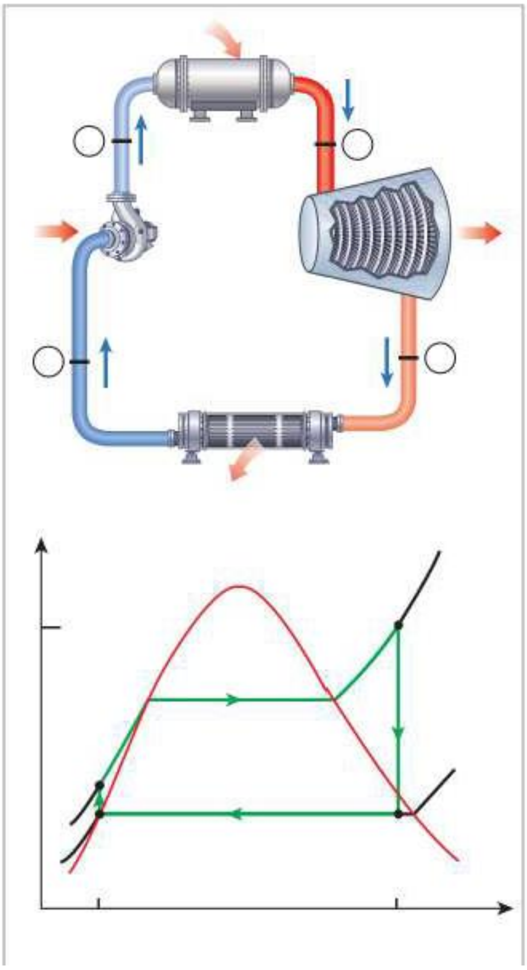
Turbine ($q = 0$): $w_{turb,out} = h_3 - h_4$

Condenser ($w = 0$): $q_{out} = h_4 - h_1$

The conversion efficiency of power plants in the United States is often expressed in terms of **heat rate**, which is the amount of heat supplied, in Btu’s, to generate 1 kWh of electricity. The smaller the heat rate, the greater the efficiency. Considering that 1 kWh = 3412 Btu and disregarding the losses associated with the conversion of shaft power to electric power

EXAMPLE 1 The Simple Ideal Rankine Cycle

Consider a steam power plant operating on the simple ideal Rankine cycle. Steam enters the turbine at 3 MPa and 350°C and is condensed in the condenser at a pressure of 75 kPa. Determine the thermal efficiency of this cycle.



SOLUTION A steam power plant operating on the simple ideal Rankine cycle is considered. The thermal efficiency of the cycle is to be determined.

Assumptions **1** Steady operating conditions exist. **2** Kinetic and potential energy changes are negligible.

State 1:

$P_1 = 75\ \text{kPa}$ Sat. liquid }
$h_1 = h_{f\,@\,75\ \text{kPa}} = 384.44\ \text{kJ/kg}$
$v_1 = v_{f\,@\,75\ \text{kPa}} = 0.001037\ \text{m}^3/\text{kg}$

State 2:

$P_2 = 3\ \text{MPa}$
$s_2 = s_1$

w pump,in
$= v_1 (P_1 - P_2) = (0.001037 \text{ m}^3/\text{kg})[(75 - 3000)$
$=- 3.03$ kJ/kg

$h_2 = h_1 - w$ pump,in $= (384.44 + 3.03)$ kJ/kg $= 387.47$ kJ/kg

State 3: $P_3 = 3$ MPa , $T_3 = 350°\text{C}$
$h_3 = 361.71465.10$ kJ/kg

State 4:
$P_4 = 75$ kPa (sat. mixture)
$s_4 = s_3$

$$x_4 = \frac{s_4 - s_f}{s_{fg}} = 0.8861$$

$h_4 = h_f + x_4 h_{fg} = 384.44 + 0.8861\,(2278.0) = 2403.0$ kJ/kg

Thus,
$q_{in} = h_3 - h_2 = (3116.1 - 387.47)$ kJ/kg $= 2728.6$ kJ/kg

$q_{out} = h_4 - h_1 = (2403.0 - 384.44)$ kJ/kg $= 2018.6$ kJ/kg

$$\eta_{Rankine} = 1 - \frac{(h_4 - h_1)}{h_3 - h_2}$$

$= 0.260$ or **26.0%**

H.W

1- simple ideal Rankine cycle with water as the working fluid operates between the pressure limits of 3 MPa in the boiler and 30 kPa in the condenser. If the quality at the exit of the turbine cannot be less than 85 percent, what is the maximum thermal efficiency this cycle can have?
Answer: 29.7 percent

2- A simple ideal Rankine cycle with water as the working fluid operates between the pressure limits of 4 MPa in the boiler and 20 kPa in the condenser and a turbine inlet temperature of 700°C. The boiler is sized to provide a steam flow of 50 kg/s. Determine the power produced by the turbine and consumed by the pump.

3- A simple ideal Rankine cycle which uses water as the working fluid operates its condenser at 40°C and its boiler at 250°C. Calculate the work produced by the turbine, the heat supplied in the boiler, and the thermal efficiency of this cycle when the steam enters the turbine without any superheating.

4- -Consider a solar-pond power plant that operates on a simple ideal Rankine cycle with refrigerant-134a as the working fluid. The refrigerant enters the turbine as a saturated vapor at 1.4 MPa and leaves at 0.7 MPa. The mass flow rate of the refrigerant is 3 kg/s. Show the cycle on a *T*-*s* diagram with respect to saturation lines, and determine (*a*) the thermal efficiency of the cycle and (*b*) the power output of this plant.

5- Consider a 210-MW steam power plant that operates on a simple ideal Rankine cycle. Steam enters the turbine at 10 MPa and 500°C and is cooled in the condenser at a pressure of 10 kPa. Show the cycle on a *T*-*s* diagram with respect to saturation lines, and determine (*a*) the quality of the steam at the turbine exit, (*b*) the thermal efficiency of the cycle, and (*c*) the mass flow rate of the steam.
Answers: (a) 0.793, (b) 40.2 percent, (c) 165 kg/s