Steam Power Plants

Objectives:

1. Classify and distinguish different plants cycles
2. Analyze basic power cycle
3. Analyze basic Rankine cycle
4. Analyze advance power cycles (reheat, regenerative and combined)

Introduction:

Thermodynamic cycles can be primarily classified based on their utility such as for power generation, refrigeration etc. Based on this thermodynamic cycles can be categorized as;

(i) Power cycles,

(ii) Refrigeration and heat pump cycles.

(i) **Power cycles:** Thermodynamic cycles which are used in devices producing power are called

power cycles. Power production can be had by using working fluid either in vapour form or in gaseous form. When vapour is the working fluid then they are called vapour power cycles, whereas in case of working fluid being gas these are called gas power cycles. Thus, power cycles shall be of two types,

(a) Vapour power cycle,

(b) Gas power cycle.

Vapour power cycles can be further classified as,

1. Carnot vapour power cycle

2. Rankine cycle

3. Reheat cycle

4. Regenerative cycle.

Gas power cycles can be classified as,

1. Carnot gas power cycle
2. Otto cycle
3. Diesel cycle
4. Dual cycle
5. Stirling cycle
6. Ericsson cycle
7. Brayton cycle

Here in the present text Carnot, Rankine, reheat and regenerative cycles are discussed.

(ii) **Refrigeration and heat pump cycles:** Thermodynamic cycles used for refrigeration and heat

pump are under this category. Similar to power cycles, here also these cycles can be classified as “air cycles” and “vapour cycles” based on type of working fluid used.

2.2 PERFORMANCE PARAMETERS

Some of commonly used performance parameters in cycle analysis are described here.

Thermal efficiency: Thermal efficiency is the parameter which gauges the extent to which the energy input to the device is converted to net work output from it.

Thermal efficiency =Net work in cycle/Heat added in cycle Heat rate:

Heat rate refers to the amount of energy added by heat transfer to cycle to produce unit net work output.

Usually energy added may be in kj, unit of net work output in W

Back work ratio: Back work ratio is defined as the ratio of pump work input (–ve work) to the work produced (+ve work) by turbine.

Back work ratio =Wpump /Wturbine Generally, back work ratio is less than one and as a designer one may be interested in developing a cycle which has smallest possible back-work ratio. Small back-work ratio indicates smaller pump work(–ve work) and larger turbine work (+ve work).

Work ratio: It refers to the ratio of net work to the positive work.

Mathematically, work ratio =Wnet/ Wturbine

Specific steam consumption: It indicates the steam requirement per unit power output. It is generally given in kg/kW. h

Specific steam consumption =Wnet/3600, kg/kW.h

2.3 CARNOT VAPOUR POWER CYCLE

Carnot cycle has already been defined earlier as an ideal cycle having highest thermodynamic efficiency. Let us use Carnot cycle for getting positive work with steam as working fluid. Arrangement proposed

for using Carnot vapour power cycle is as follows.

1 – 2 = Reversible isothermal heat addition in the boiler

2 – 3 = Reversible adiabatic expansion in steam turbine

3 – 4 = Reversible isothermal heat rejection in the condenser

4 – 1 = Reversible adiabatic compression or pumping in feed water pump

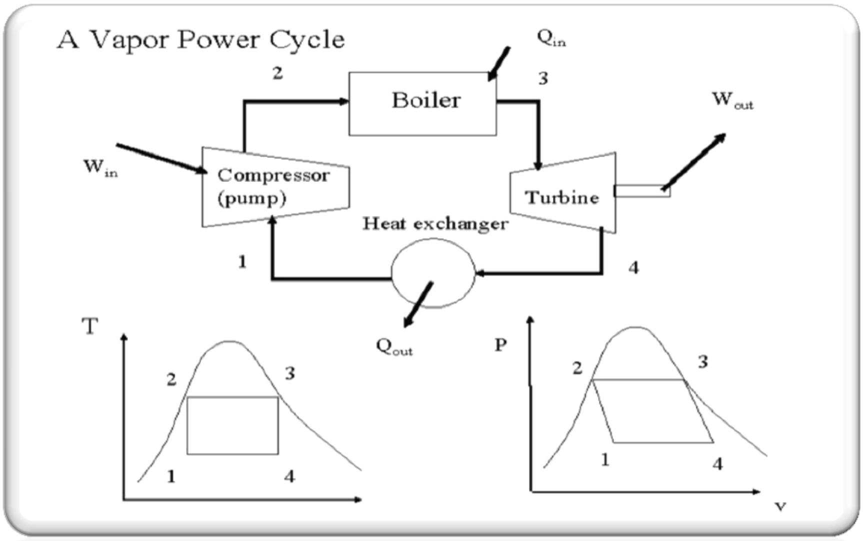


Fig 1.1

Arrangement for Carnot cycle

Assuming steady flow processes in the cycle and neglecting changes

$$\text{Thermal efficiency} = \frac{\text{Net work}}{\text{Heat added}}$$

Net work = Turbine work – Compression/Pumping work

For unit mass flow.

$$W = (h_2 - h_3) - (h_1 - h_4)$$

$$\text{Heat added, } Q_{\text{add}} = (h_2 - h_1)$$

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

$$= 1 - \frac{h_3 - h_4}{h_2 - h_1}$$

Here heat rejected, $Q_{\text{rejected}} = (h_3 - h_4)$

or $\eta_{\text{Carnot}} = 1 - \dfrac{Q_{\text{rejected}}}{Q_{\text{add}}}$

Also, heat added and rejected may be given as function of temperature and entropy as follows:

$$Q_{\text{add}} = T_1 \times (s_2 - s_1)$$

$$Q_{\text{rejected}} = T_3 \times (s_3 - s_4)$$

Also, $s_1 = s_4$ and $s_2 = s_3$

Therefore, substituting values: $\eta_{\text{Carnot}} = 1 - \dfrac{T_3}{T_1}$

or $\eta_{\text{Carnot}} = 1 - \dfrac{T_{\text{minimum}}}{T_{\text{maximum}}}$

Let us critically evaluate the processes in Carnot cycle and see why it is not practically possible.

in kinetic and potential energies,thermodynamic analysis may be carried out.

Thermal analysis for Carnot cycle:

$$\text{Thermal efficiency} = \frac{\text{Net work}}{\text{Heat added}}$$

$$\text{Net work} = \text{Turbine work} - \text{Compression/Pumping work}$$

The network for unit mass flow:

$$Wnet = W_T - W_p$$

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

For Boiler:

$$Q_{add} = (h_3 - h_2)$$

For Condenser:

$$Q_{rejected} = (h_4 - h_1)$$

The thermal efficiency:

$$\eta = \frac{W_{net}}{Q_{add}}$$

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

$$\eta = 1 - \frac{Q_{rejected}}{Q_{add}}$$

The heat added and rejected can be given as function of temperature and entropy as follows:

Since : $Q = T\Delta s$

$$Q_{add} = T_2(s_3 - s_2)$$

$$Q_{rejected} = T_1(s_4 - s_1)$$

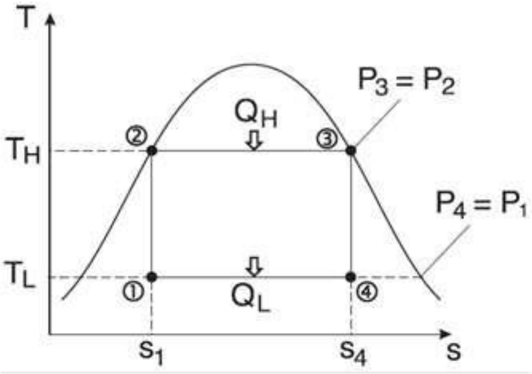
Also : $s_1 = s_2$ and $s_3 = s_4$

$$\eta = 1 - \frac{T_1}{T_2}$$

EXAMPLE 1

A Carnot cycle works on steam between the pressure limits of 7 MPa and 7 kPa. Determine thermal efficiency, turbine work and compression work per kg of steam.

SOLUTION:



Enthalpy at state 3, $h_3 = h_{g \text{ at } 7\text{ MPa}}$

$$h_3 = 2772.1 \text{ kJ/kg}$$

Entropy at state 2, $s_3 = s_{g \text{ at } 7\text{ MPa}}$

$$s_3 = 5.8133 \text{ kJ/kg} \cdot \text{K}$$

Enthalpy and entropy at state 2,

$$h_2 = h_{f \text{ at } 7\text{ MPa}} = 1267 \text{ kJ/kg}$$

$$s_2 = s_{f \text{ at } 7\text{ MPa}} = 3.1211 \text{ kJ/kg} \cdot \text{K}$$

For process 3 – 4, $s_3 = s_4$ Let dryness fraction at state 4 be x_4

$$s_3 = s_4 = s_{f \text{ at } 7\text{ kPa}} + x_4 \cdot s_{fg \text{ at } 7\text{ kPa}}$$

$$5.8133 = 0.5564 + x_4 \cdot 7.7237$$

$$x_4 = 0.6806$$

Enthalpy of state 4, $h_4 = h_{f \text{ at } 7\text{ kPa}} + x_4 \cdot h_{fg \text{ at } 7\text{ kPa}}$

$$= 162.60 + (0.6806 \times 2409.54)$$

$$h_4 = 1802.53 \text{ kJ/kg}$$

Let dryness fraction at state 1 be x_1,

For process 1–2, $s_1 = s_2 = s_{f \text{ at } 7\text{ kPa}} + x_1 \cdot s_{fg \text{ at } 7\text{ kPa}}$

$$3.1211 = 0.5564 + x_1 \cdot 7.7237$$

$$x_1 = 0.3321$$

$$\text{Enthalpy at state 1, } h_1 = h_{f \text{ at 7 kPa}} + x_1 \cdot h_{fg \text{ at 7 kPa}}$$

$$= 162.60 + (0.3321 \times 2409.54)$$

$$h_1 = 962.81 \text{ kJ/kg}$$

$$\text{Thermal efficiency} = \frac{\text{Net work}}{\text{Heat added}}$$

$$\text{Expansion work per kg} = h_3 - h_4 = (2772.1 - 1802.53) = 969.57 \text{ kJ/kg}$$

$$\text{Compression work per kg} = h_2 - h_1 = (1267 - 962.81)$$

$$= 304.19 \text{ kJ/kg (+ve)}$$

$$\text{Heat added per kg} = h_3 - h_2 = (2772.1 - 1267)$$

$$= 1505.1 \text{ kJ/kg (–ve)}$$

$$\text{Net work per kg} = (h_3 - h_4) - (h_2 - h_1) = 969.57 - 304.19$$

$$= 665.38 \text{ kJ/kg}$$

$$\text{Thermal efficiency} = \frac{665.38}{1505.1} = 0.4421 \text{ or } 44.21\%$$

H.W

1- A Carnot cycle works on steam between the pressure limits of 7 MPa and 7 kPa. Determine thermal efficiency, turbine work and compression work per kg of steam.
Answers: Thermal efficiency = 44.21%, Turbine work = 969.57 kJ/kg (+ve),Compression work = 304.19 kJ/kg (–ve)

2- Consider a steady-flow Carnot cycle with water as the working fluid. The maximum and minimum temperatures in the cycle are 350 and 60°C. The quality of water is 0.891 at the beginning of the heat-rejection process and 0.1 at the end. Show the cycle on a *T*-*s* diagram relative to the saturation lines, and determine (*a*) the thermal efficiency, (*b*) the pressure at the turbine inlet, and (*c*) the net work output.
Answers: (*a*) 0.465, (*b*) 1.40 MPa, (*c*) 1623 kJ/kg

3- Determine the net work output and the thermal efficiency for the Carnot cycle with steam as the working fluid. Steam enters the turbine in both cases at 10 MPa as a saturated vapor, and the condenser pressure is 20 kPa. In the Carnot cycle, the boiler inlet state is saturated liquid. Draw the *T*-*s* diagrams
for this cycle.
Answers: 565.4 kJ/kg , 43%