

Basic Thermodynamics

Cycle analysis

Objectives and other details of modules

Duration – 90 minutes

Training aids

Power point Presentations

Reading Material

Objective

At the end of the session participants will be able to:

- **Recap the basic thermodynamics, laws and thermodynamics cycles and its application in thermal power generation**
- **Effect various parameters on the cycle performance**
- **Undertake thermal cycle analysis and efficiency calculation**

Thermodynamic laws

Basic Thermodynamics

The four **laws of thermodynamics** define fundamental physical quantities (temperature, energy, and entropy) that characterize thermodynamic systems. The laws describe how these quantities behave under various circumstances, and forbid certain phenomena (such as perpetual motion).

The four laws of thermodynamics are:

From the above, all the energy associated with a system must be accounted for as heat, work, chemical energy etc., thus perpetual motion machines of the first kind, which would do work without using the energy resources of a system, are impossible.

If two systems are both in thermal equilibrium with a third system then they are in thermal equilibrium with each other. This law helps define the notion of temperature.

Zeroeth Law

There is a state function, called temperature which has the symbol T , which has the following relationship to heat, q :

addition of heat to a system will increase the temperature of the system.

if two closed system (together isolated), with different temperatures are brought into thermal contact, then the temperatures of the two systems will change to approach the same temperature.

That is, the temperature of the system which is at a higher temperature will decrease and the temperature of the system with the lower temperature will increase. They will eventually have the same temperature.

First Law of thermodynamics

Use of internal energy or change in internal energy, ΔE , is not very convenient in chemistry. The reason for this is that when chemical reactions occur or samples are heated, the volume does not stay constant. If one is therefore interested in only q , the ΔE is complicated by an additional w . To avoid this a new quantity called enthalpy is defined, given the symbol H .

$$H = E + PV \text{ or}$$

$$\Delta H = \Delta E + P\Delta V$$

Since at constant pressure $P\Delta V = -w$ if no other external form of work is present, then:

$$\Delta H = w + q + P\Delta V$$

and

$$\Delta H = q$$

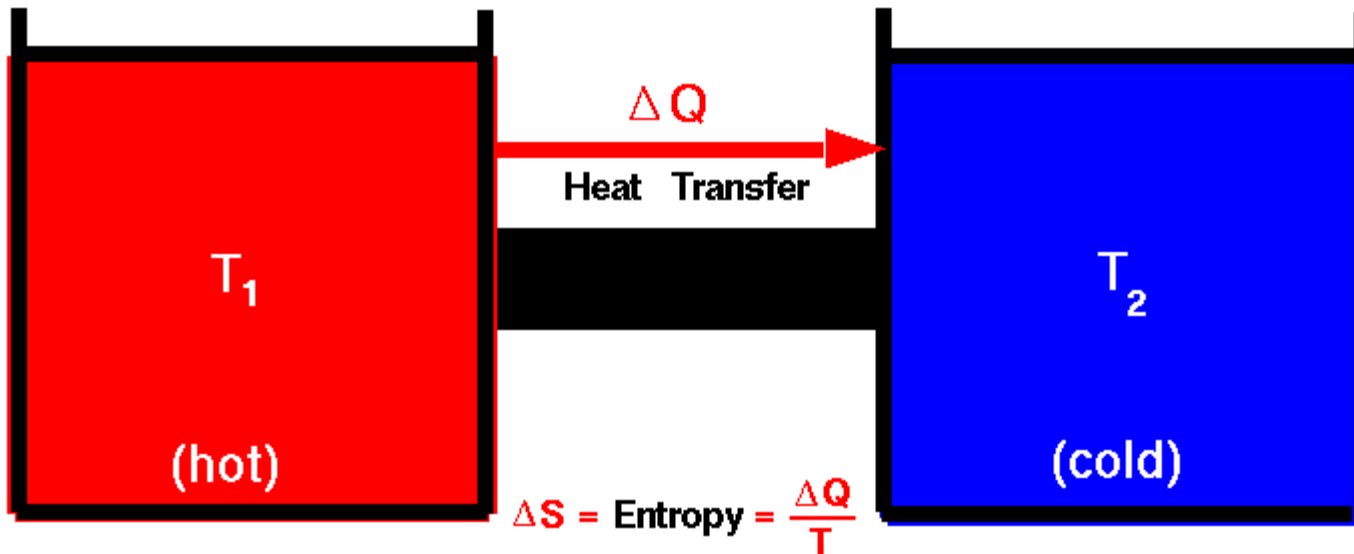
Therefore at constant pressure ΔH will yield the heat transferred. All thermodynamic tables use this as the tabulated "heat of reaction," etc.

Second Law of Thermodynamics



Second Law of Thermodynamics

Glenn
Research
Center

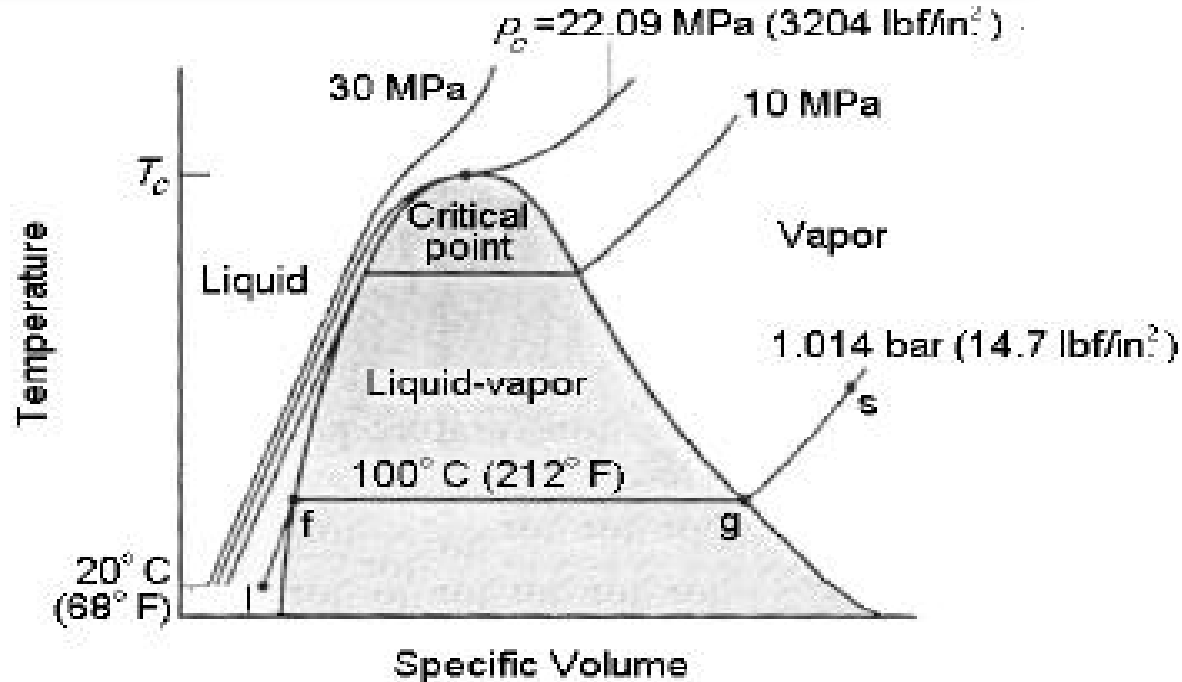


There exists a useful thermodynamic variable called entropy (S). A natural process that starts in one equilibrium state and ends in another will go in the direction that causes the entropy of the system plus the environment to increase for an irreversible process and to remain constant for a reversible process.

$$S_f = S_i \text{ (reversible)}$$

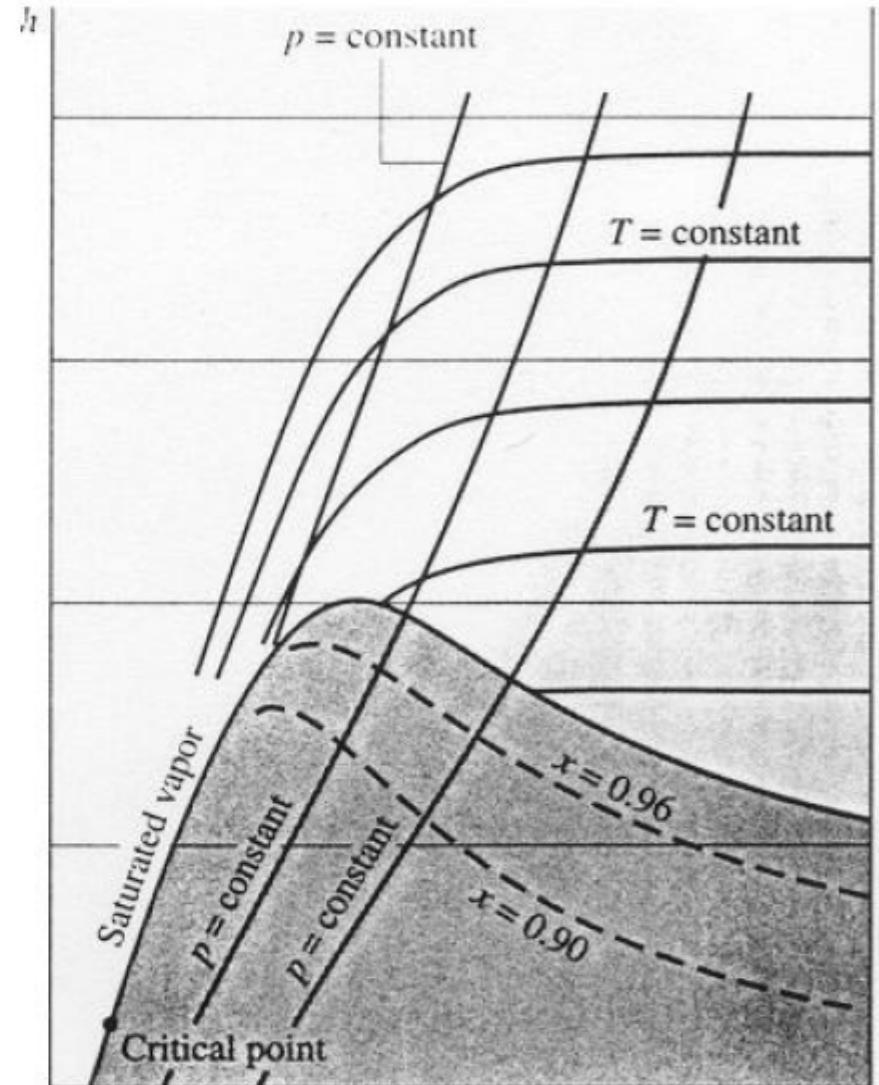
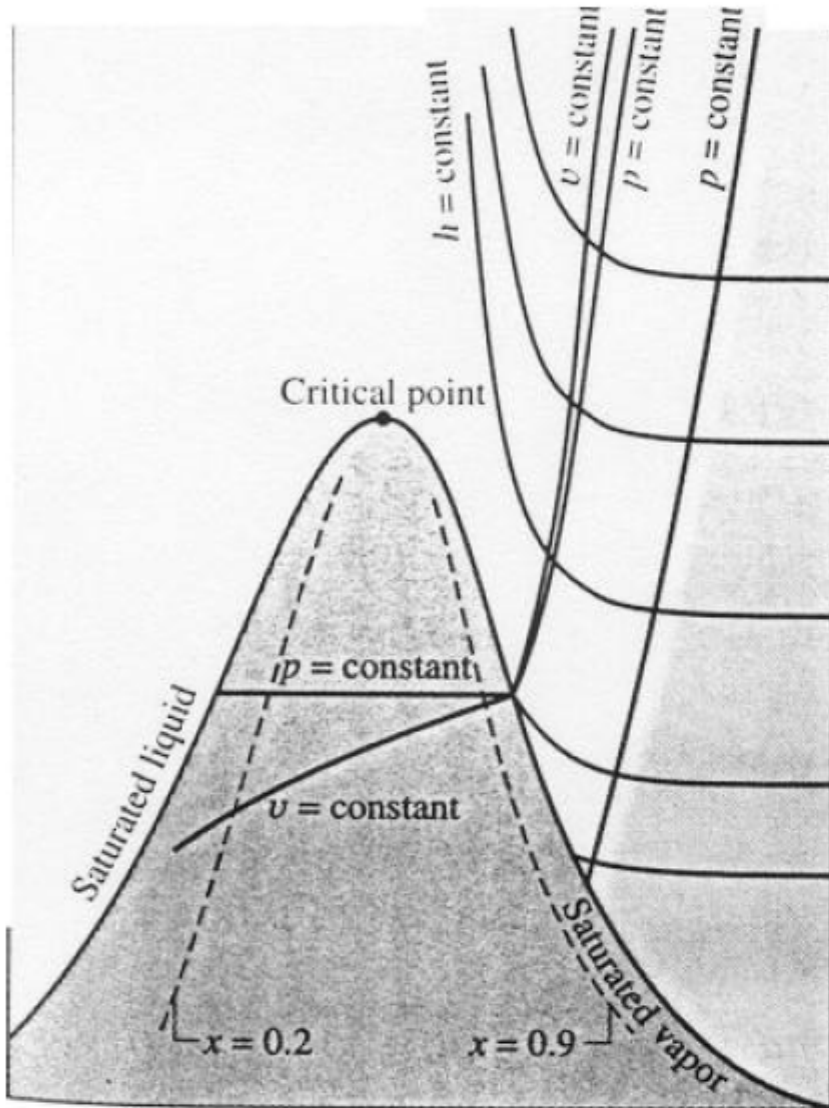
$$S_f > S_i \text{ (irreversible)}$$

Vapor dome

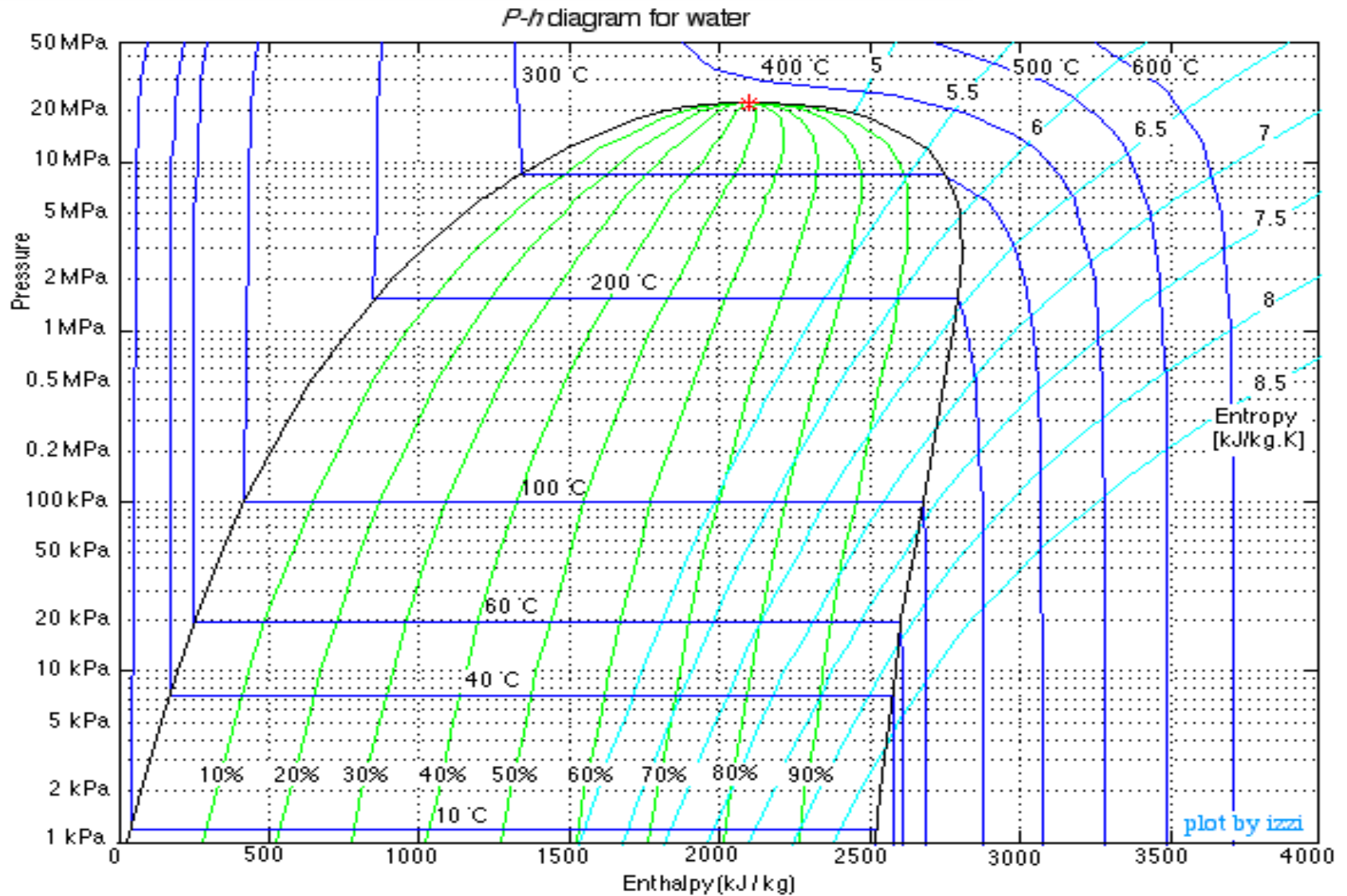


Critical State: Saturated liquid and saturated vapor states are identical. The two phases are indistinguishable. [Water: $p_c = 22.09 \text{ MPa}$ & $T_c = 647.3 \text{ K}$], The critical point is the tip of the vapor dome.

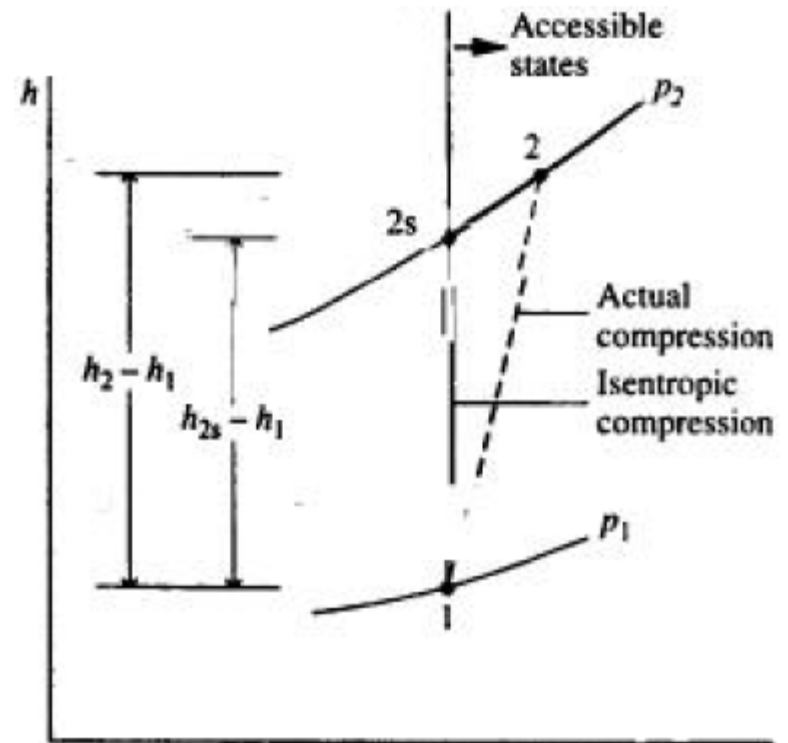
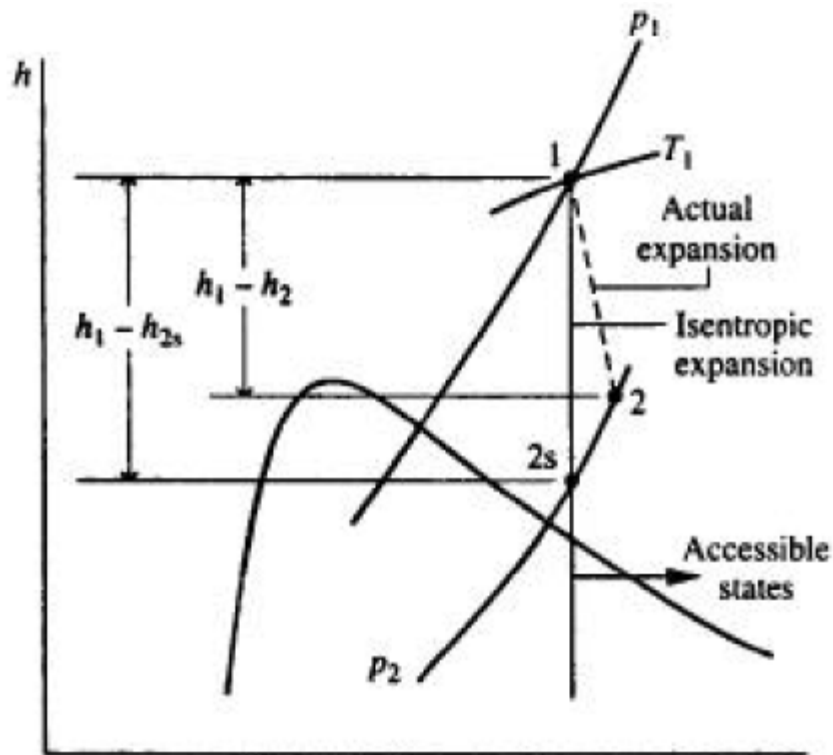
Mollier chart



Pressure-enthalpy diagram



Isentropic and actual process



Carnot Cycle

Carnot Cycle

Four processes.

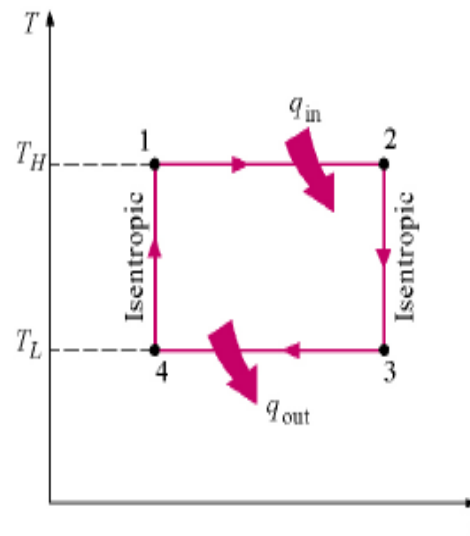
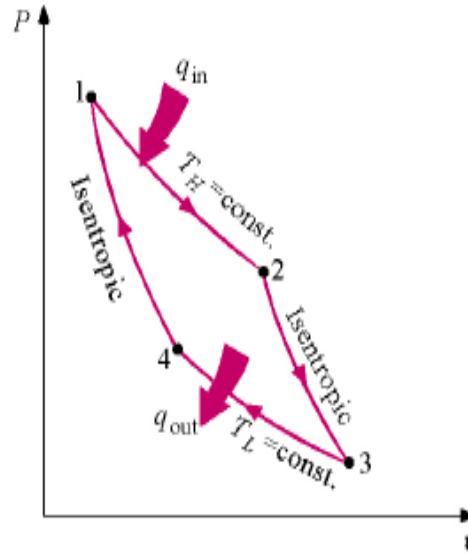
- 1-2 Isothermal Heat Addition
- 2-3 Isentropic Expansion
- 3-4 Isothermal Heat Rejection
- 4-1 Isentropic Compression

The **net cycle work** done is the area enclosed by the cycle on the P-v diagram.

The **net heat added** is the area enclosed by the cycle on the T-s diagram.

For a cycle $W_{net} = Q_{net}$, the areas on the P-v and T-s diagrams are equal.

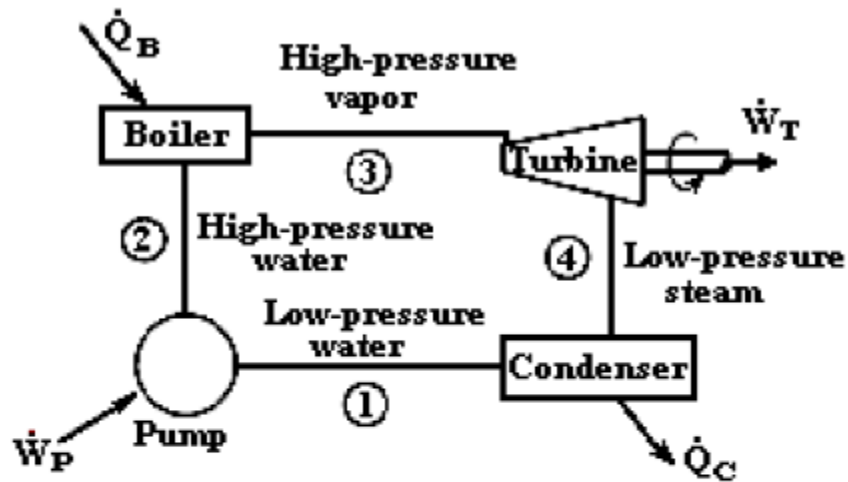
$$\eta_{th, Carnot} = 1 - \frac{T_L}{T_H}$$



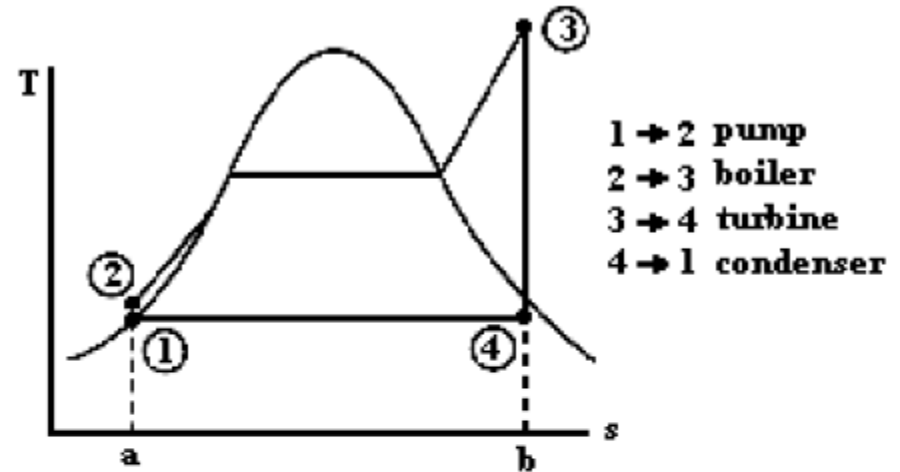
Sadi Carnot (1796 - 1832)

Rankine Cycle

⊕ Rankine Cycle:



(a) The Major Components

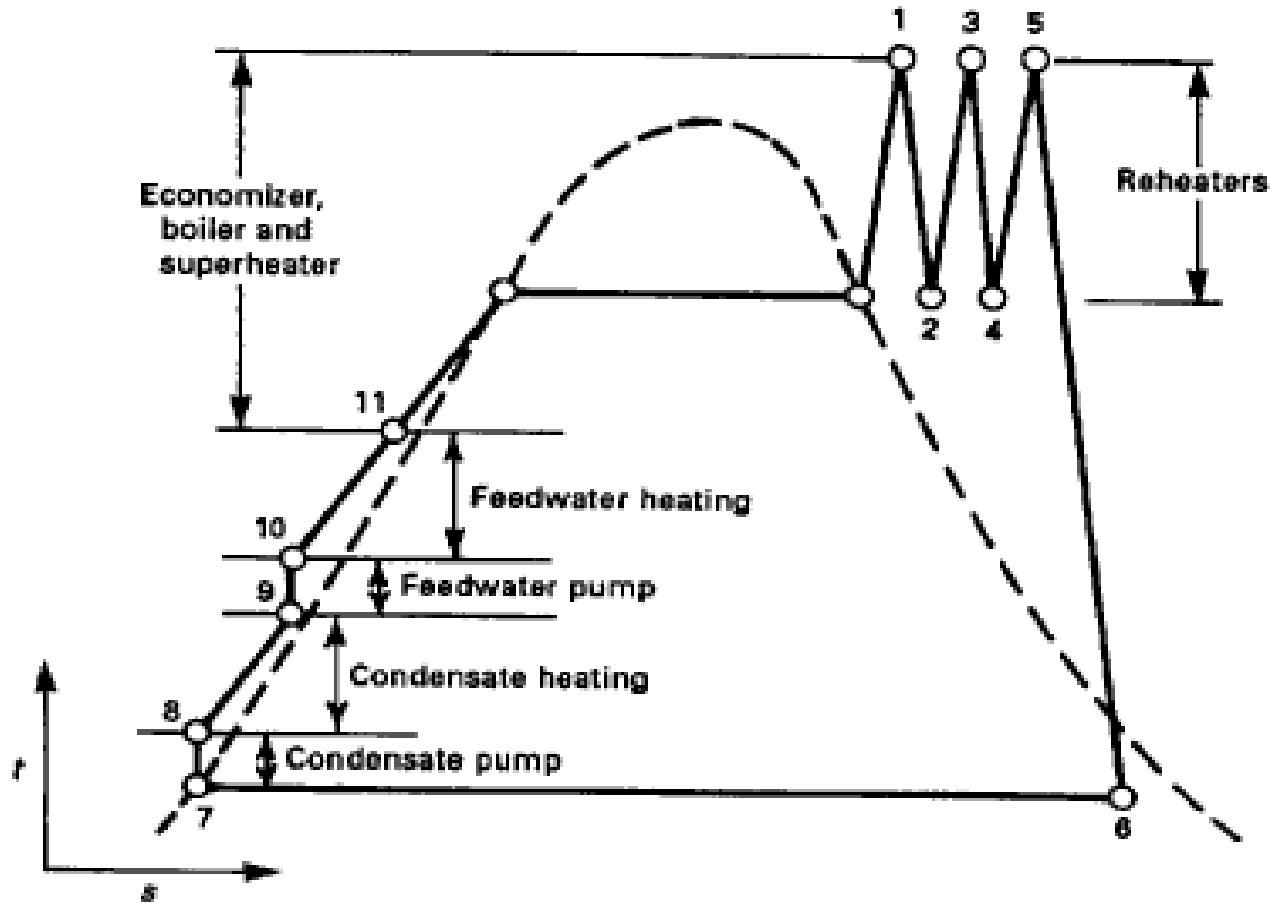


(b) The T - s diagram

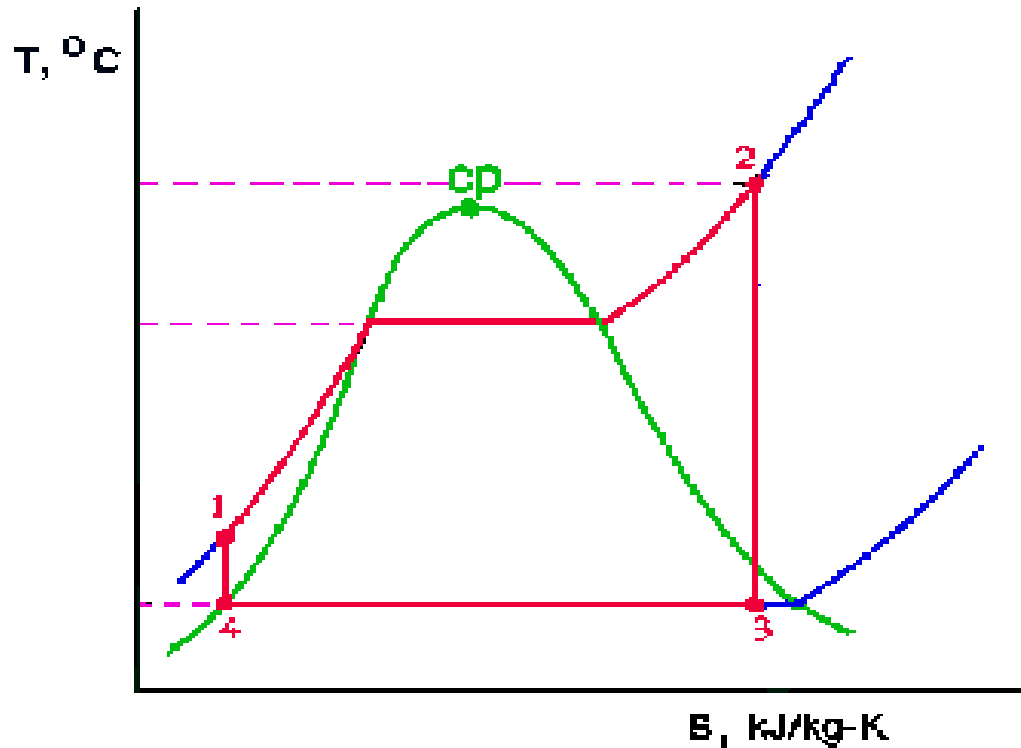
A useful diagram is a plot displaying temperature versus entropy (T - s diagram).

- (1)→(2): pump isentropic compression
- (2)→(3): boiler constant pressure heat addition
- (3)→(4): turbine isentropic expansion
- (4)→(1): condenser constant pressure heat rejection.

Rankine Cycle



Efficiency of Rankine cycle



$$q_{\text{absorb}} = h_2 - h_1$$

$$q_{\text{exhaust}} = h_3 - h_4$$

$$\begin{aligned} \eta &= \frac{q_{\text{absorb}} - q_{\text{exhaust}}}{q_{\text{absorb}}} \\ &= \frac{h_2 - h_1 - (h_3 - h_4)}{h_2 - h_1} \\ &= \frac{h_2 - h_1 - h_3 + h_4}{h_2 - h_1} \end{aligned}$$

Turbine analysis

adiabatic no kinetic or potential energy

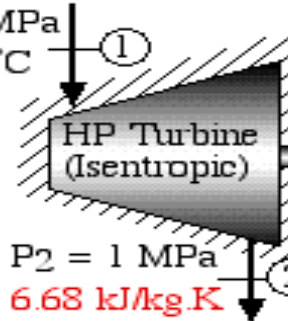
$$q_1 - w = \Delta h + \Delta ke + \Delta pe$$

$$h_1 = 3583 \text{ kJ/kg}$$

$$s_1 = 6.68 \text{ kJ/kg.K}$$

$$P_1 = 15 \text{ MPa}$$

$$T_1 = 600^\circ\text{C}$$



$$w_{HP} = h_1 - h_2$$

$$= 762 \text{ kJ/kg}$$

$$P_2 = 1 \text{ MPa}$$

$$s_2 = s_1 = 6.68 \text{ kJ/kg.K}$$

s	6.585	6.680	6.696	kJ/kg.K
h	2777	2821	2828	kJ/kg
T	180°C	197°C	200°C	

Linear interpolation from superheat steam tables

$$w_T = w_{HP} + w_{LP}$$

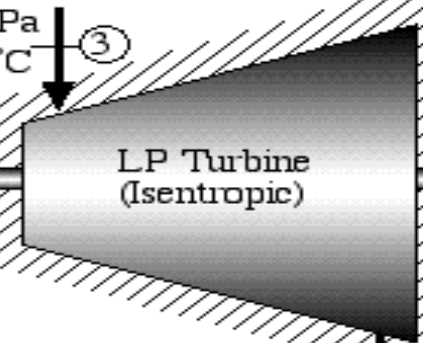
$$= 1925 \text{ kJ/kg}$$

$$h_3 = 3699 \text{ kJ/kg}$$

$$s_3 = 8.031 \text{ kJ/kg.K}$$

$$P_3 = 1 \text{ MPa}$$

$$T_3 = 600^\circ\text{C}$$



$$w_{LP} = h_3 - h_4$$

$$= 1163 \text{ kJ/kg}$$

$$P_4 = 10 \text{ kPa}$$

$$s_4 = s_3 = 8.031 \text{ kJ/kg.K} < s_{g@10kPa} = 8.1488 \text{ kJ/kg.K}$$

thus: State 4 is in the Quality region

$$T_4 = T_{sat@10kPa} = 46^\circ\text{C}$$

$$\text{quality: } X = \left[\frac{s - s_f}{s_{fg}} \right] = \left[\frac{h - h_f}{h_{fg}} \right]$$

$$s_f = 0.6492 \text{ kJ/kg.K}, s_{fg} = 7.500 \text{ kJ/kg.K}$$

$$X_4 = 0.98$$

$$h_f = 192 \text{ kJ/kg}, h_{fg} = 2392 \text{ kJ/kg}$$

$$h_4 = 2536 \text{ kJ/kg}$$

Pump work

In this ideal cycle we assume that the feedwater pump is isentropic. Furthermore, since the suction temperature of the water is 46°C, we assume that it behaves as an incompressible liquid, even at 15 MPa

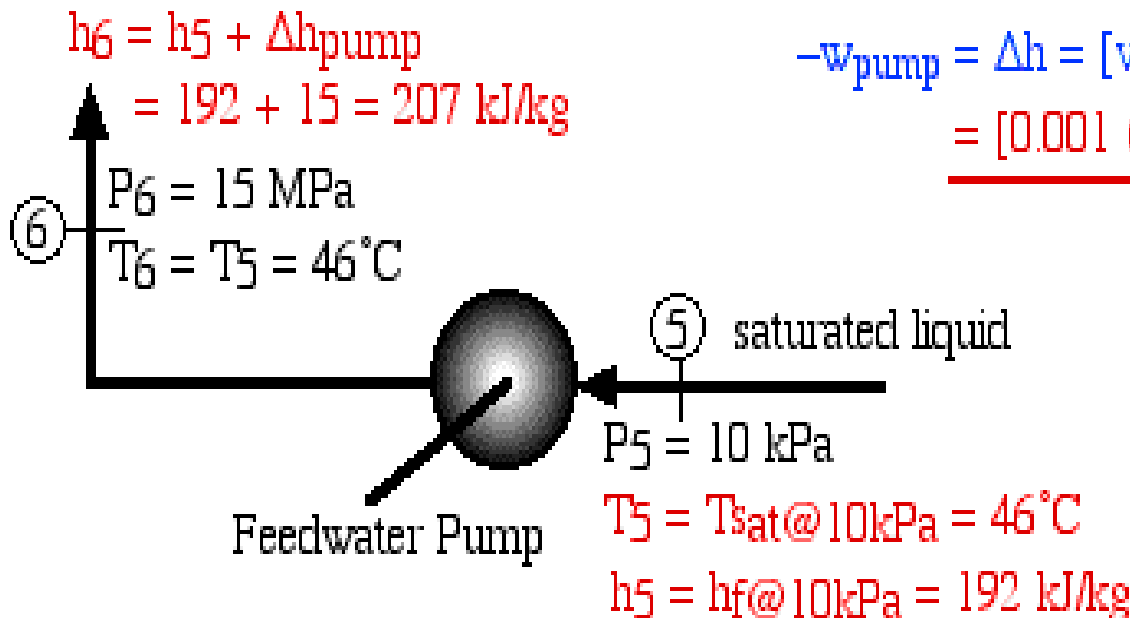
adiabatic no kinetic or potential energy

$$q_1 - w = \Delta h + \Delta ke + \Delta pe$$

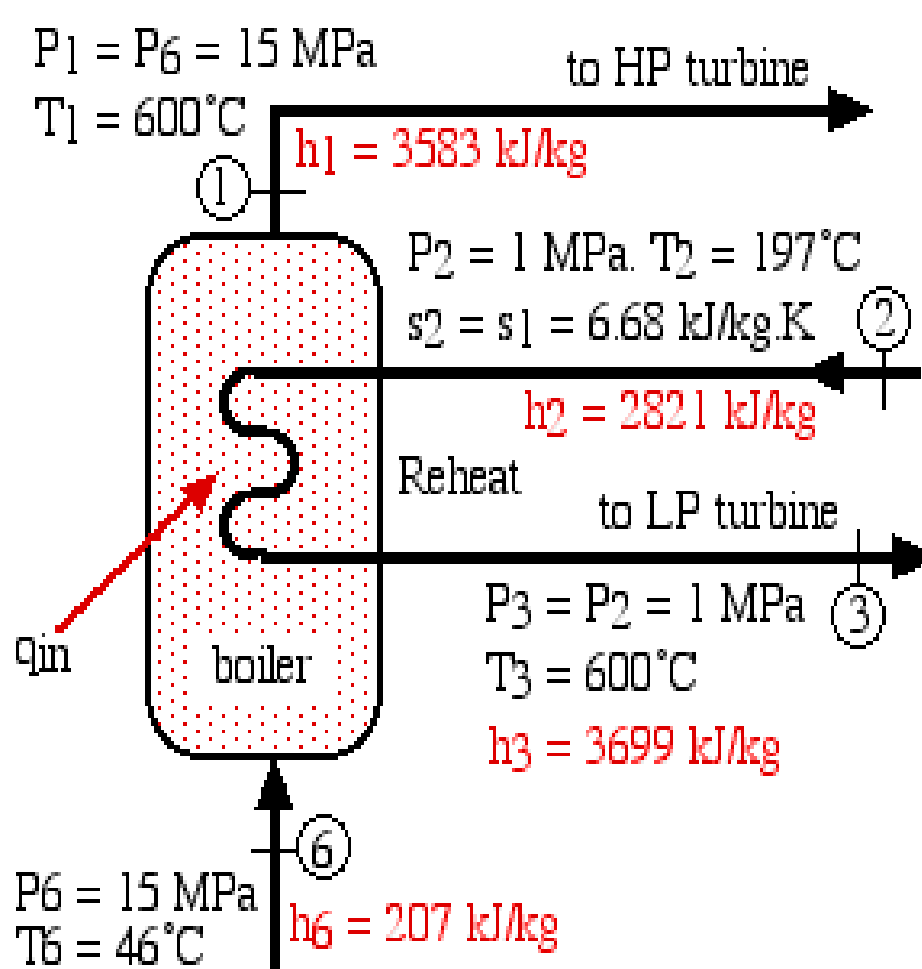
Assume incompressible liquid: $\Delta T = 0$

$$-w_{\text{pump}} = \Delta h = [v \Delta P + C_{\text{H}_2\text{O}} \Delta T]$$

$$= [0.001 (15,000 - 10)] = 15 \text{ kJ/kg}$$



Boiler

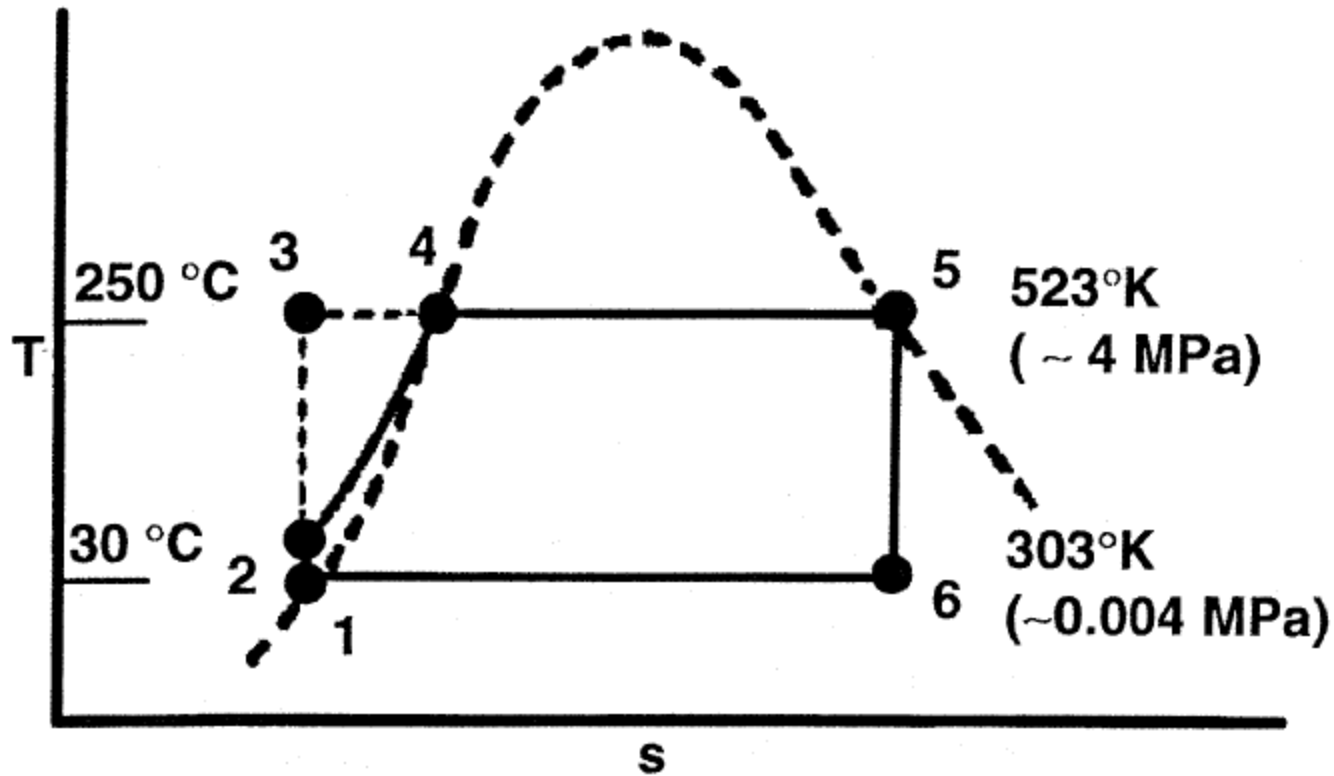


no work no kinetic or potential energy

$$q - w = \Delta h + \Delta ke + \Delta pe$$

$$\begin{aligned}
 q_{in} &= \Delta h = (h_1 - h_6) + (h_3 - h_2) \\
 &= (3376 + 878) \text{ kJ/kg} \\
 &= 4254 \text{ kJ/kg}
 \end{aligned}$$

Carnot and Rankin cycle



Carnot and Rankin cycle

Carnot Cycle 1 - 3 - 5 - 6

$$\eta = \frac{T_H - T_C}{T_H} = \frac{523 - 303}{523} = \frac{220}{523} = 0.42 = 42\%$$

Rankine Cycle 1 - 2 - 4 - 5 - 6

$$h_1 = 126 \quad \text{kJ/kg}$$

$$h_2 = 130 \quad \text{kJ/kg}$$

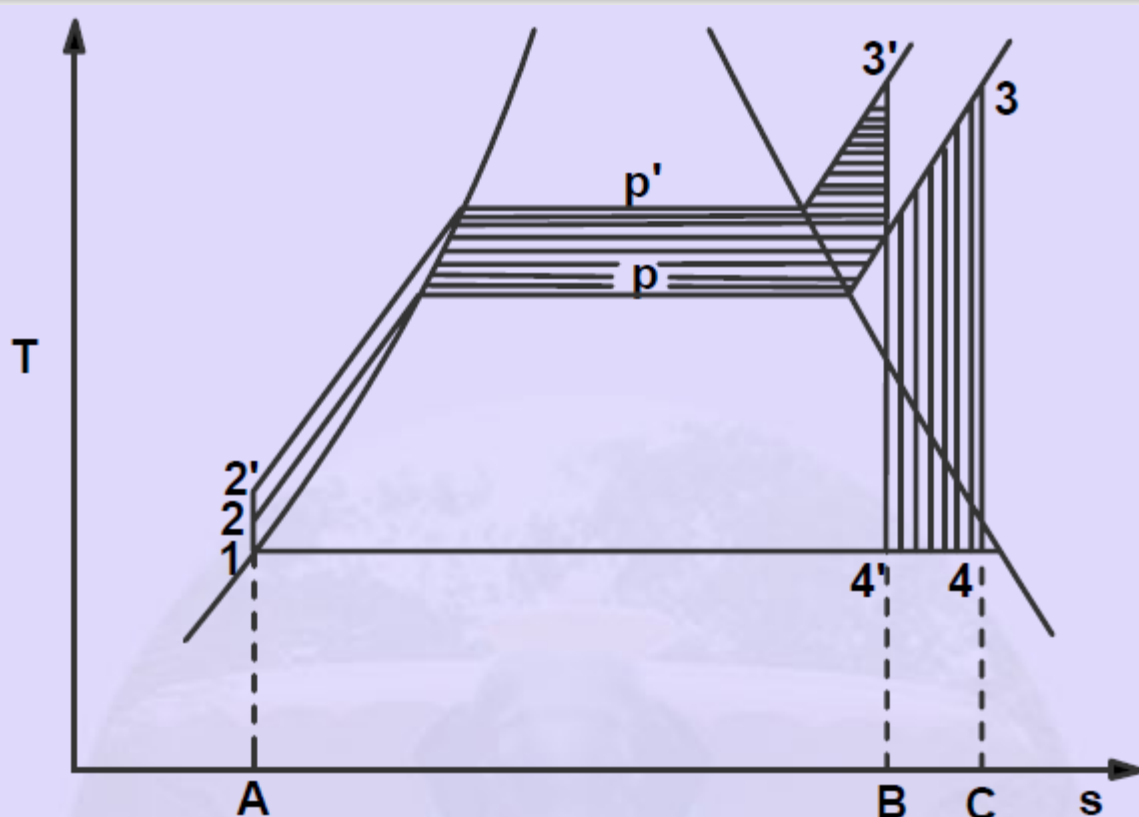
$$h_4 = 535 \quad \text{kJ/kg}$$

$$h_5 = 2802 \quad \text{kJ/kg}$$

$$h_6 = 1835 \quad \text{kJ/kg}$$

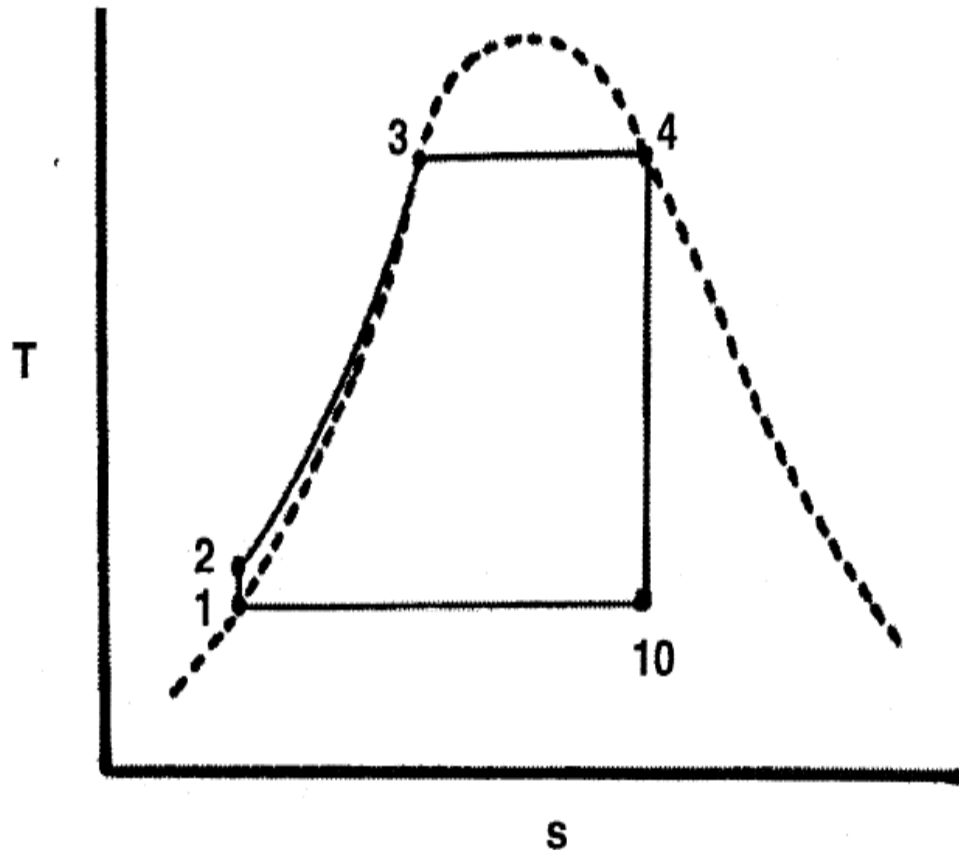
$$\eta = \frac{h_5 - h_6}{h_5 - h_2} = \frac{2802 - 1835}{2802 - 130} = \frac{976}{2676} = 0.36 = 36\%$$

Effect of increase in pressure



The two cycles are shown above 1-2-3-4-1 and 1-2'-3'-4'-1 have the same minimum pressure but different maximum pressures. As the result of increasing the maximum pressure from p to p' , the net work output has increased by the area shown by horizontal hatching and decreased by the area shown by vertical hatching. Since, these two areas are nearly equal, the network is nearly the same, but the net heat rejected decreases by the area 4'-4-C-B. Hence, the thermal efficiency increases.

Rankin cycle saturated



Heat Input

$$q_{in} = (h_4 - h_2)$$

Work Output

$$w = (h_4 - h_{10})$$

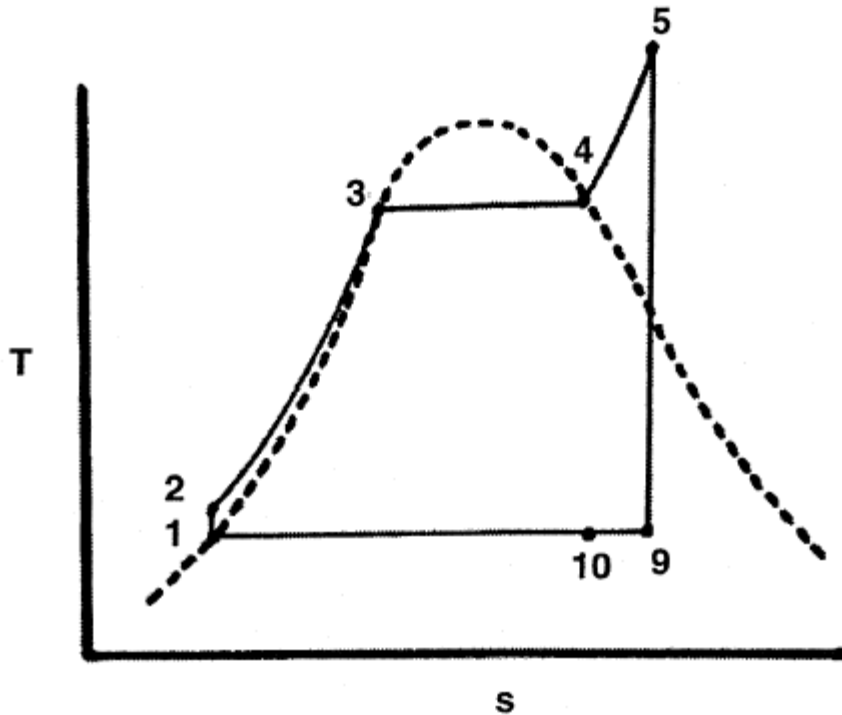
Pump Work

$$w = (h_2 - h_1)$$

Efficiency

$$\eta = \frac{(h_4 - h_{10}) - (h_2 - h_1)}{(h_4 - h_2)}$$

Rankin cycle-Super heated



Heat Input

$$q_{in} = (h_5 - h_2)$$

Work Output

$$w = (h_5 - h_9)$$

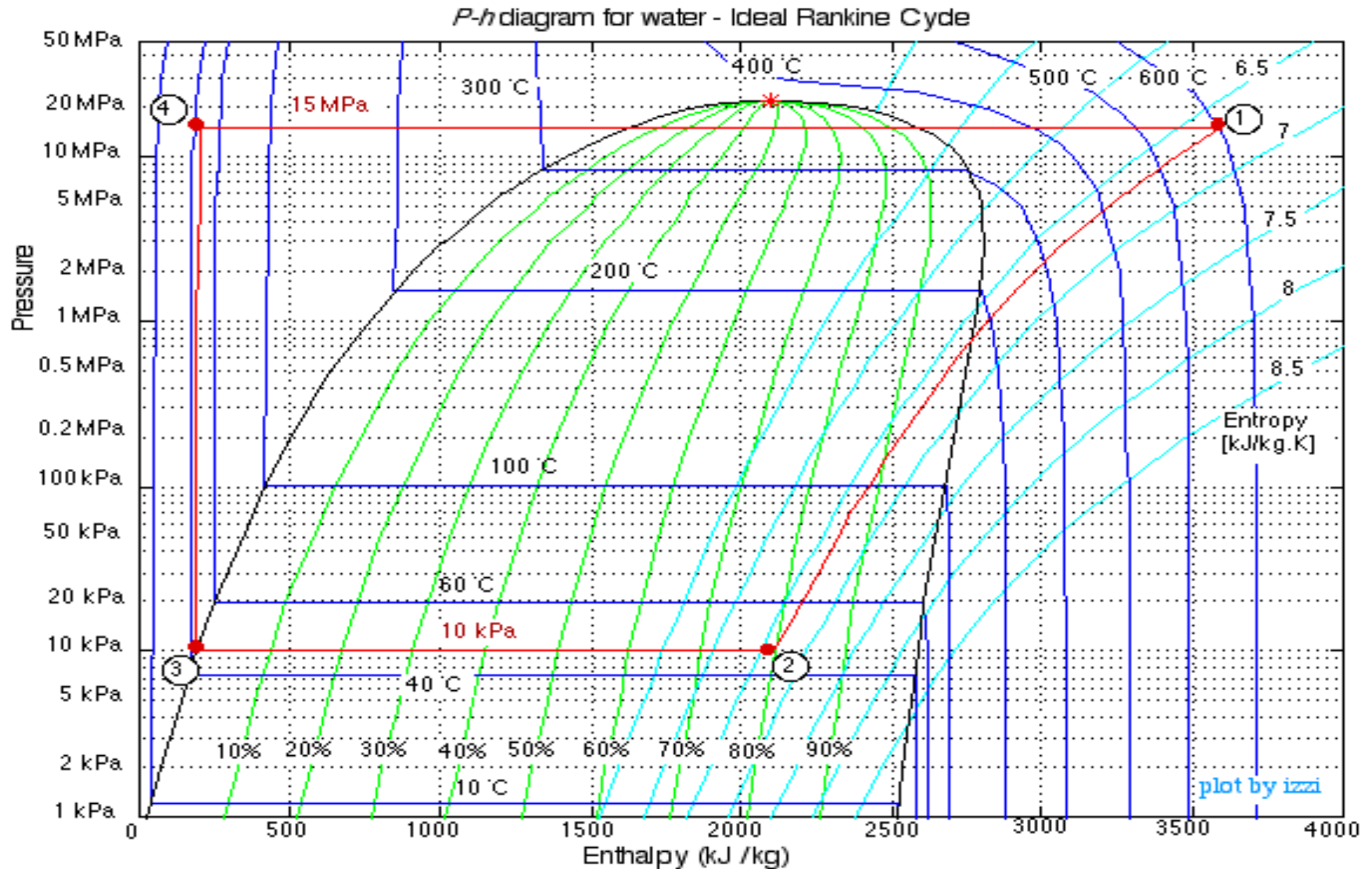
Pump Work

$$w = (h_2 - h_1)$$

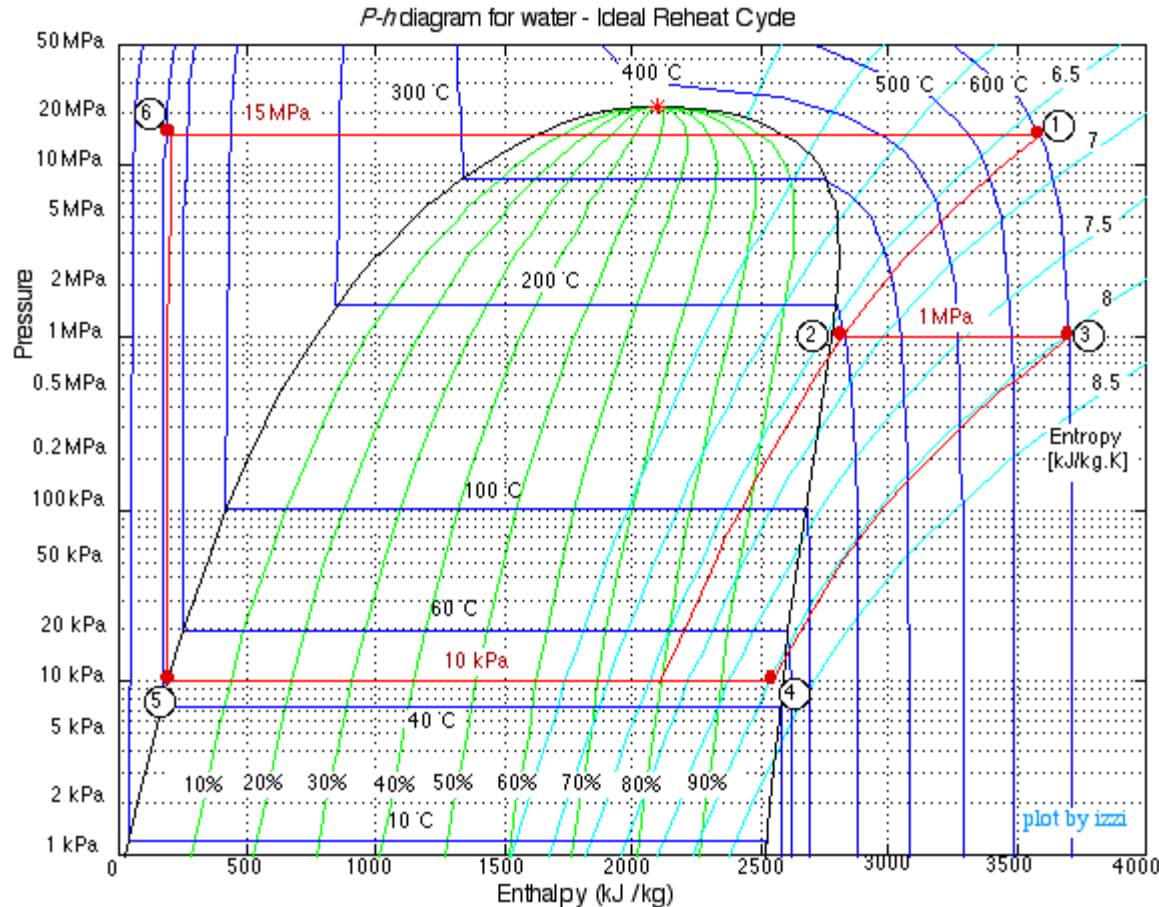
Efficiency

$$\eta = \frac{(h_5 - h_9) - (h_2 - h_1)}{(h_5 - h_2)}$$

Cycle with out Reheating

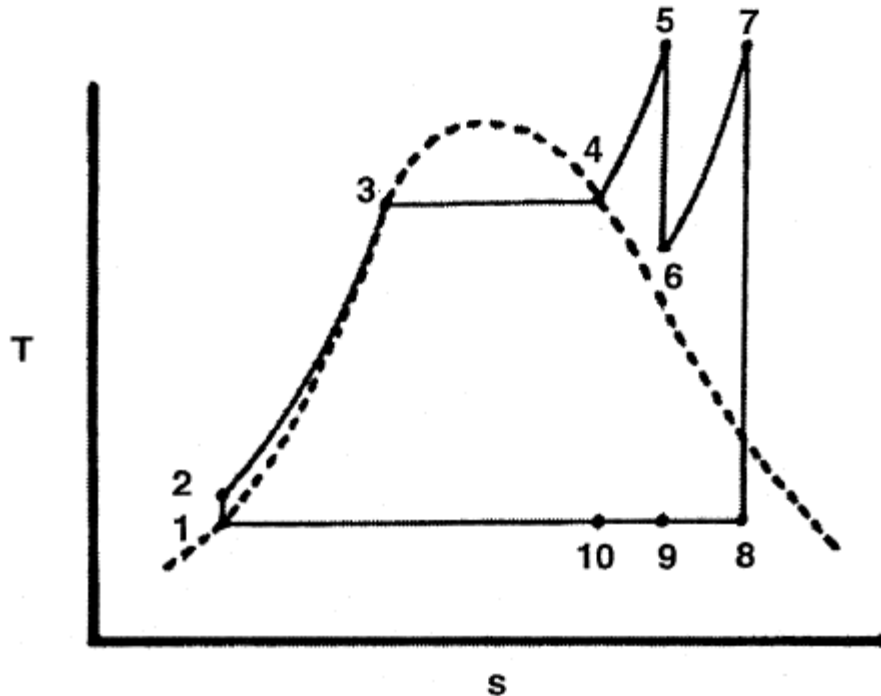


Effect of Reheating



We notice that reheating the output of the HP turbine back to 600°C (process (2)-(3)) allows both significantly more power output as well as increasing the quality at the LP turbine output (4) to 98%.

Rankin cycle -reheated



Heat Input

$$q_{in} = (h_7 - h_6) + (h_5 - h_2)$$

Work Output

$$w = (h_5 - h_6) + (h_7 - h_8)$$

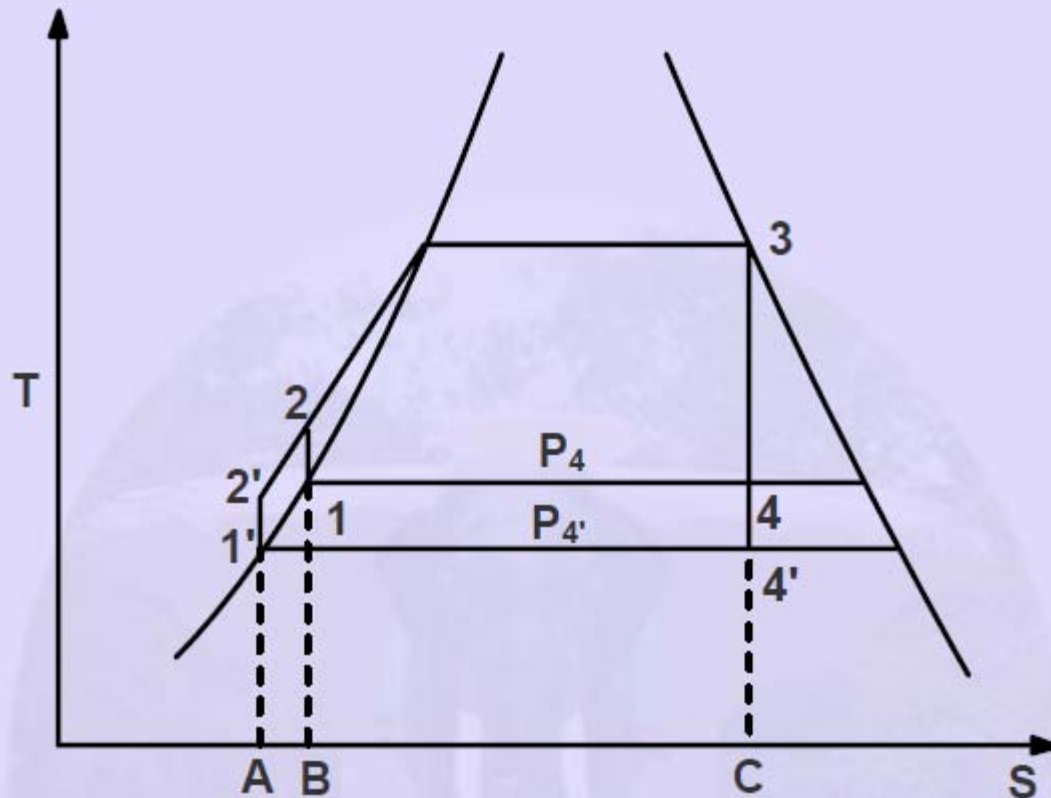
Pump Work

$$w = (h_2 - h_1)$$

Efficiency

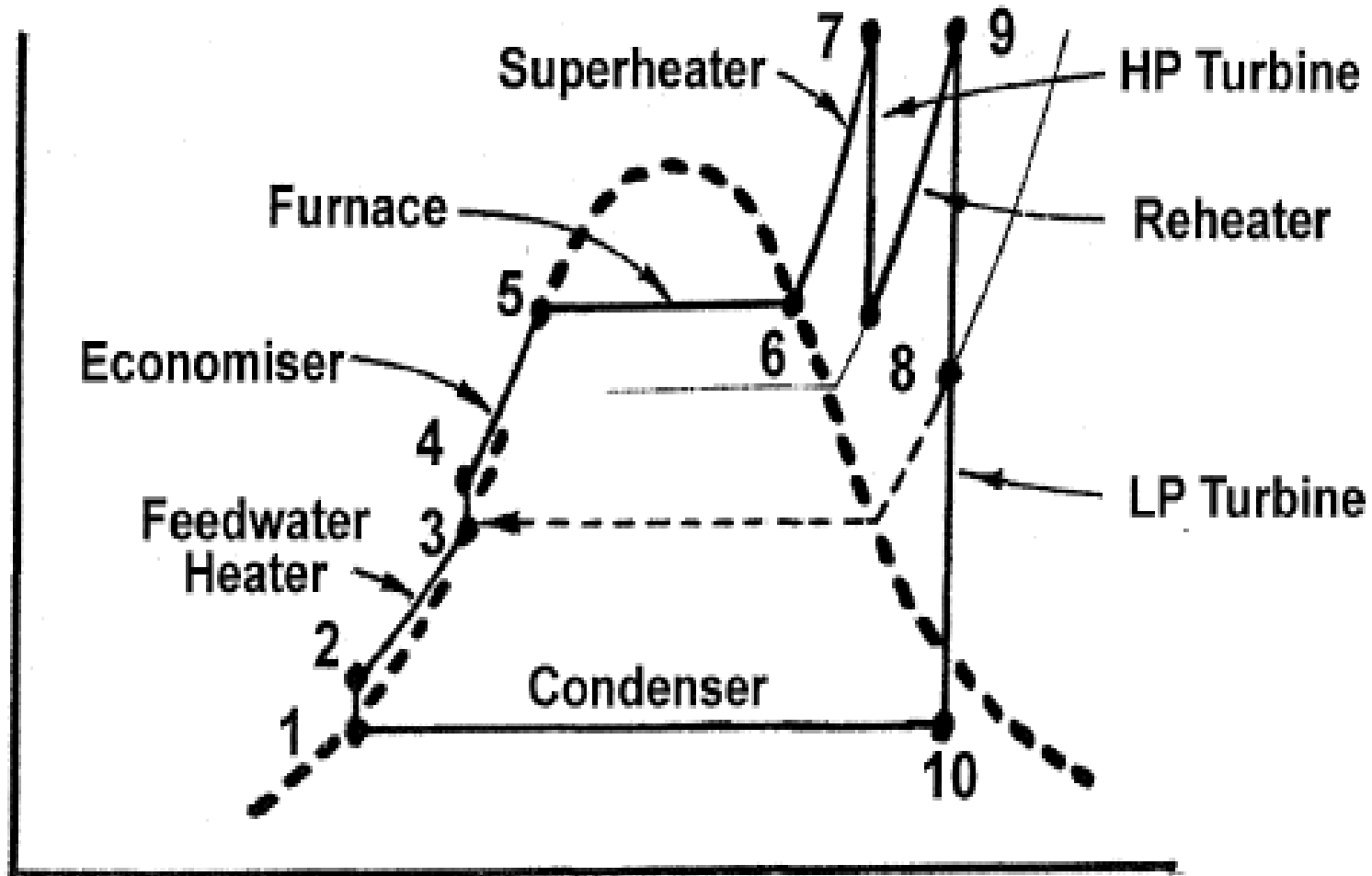
$$\eta = \frac{(h_5 - h_6) + (h_7 - h_8) - (h_2 - h_1)}{(h_7 - h_6) + (h_5 - h_2)}$$

Effect of condenser pressure

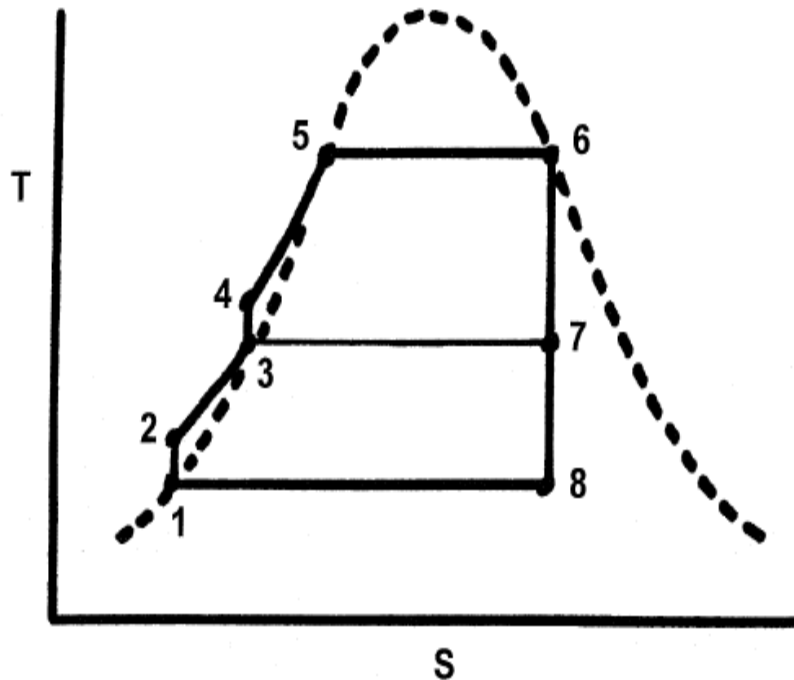


If the condenser pressure is reduced from p_4 to $p_{4'}$, the net work is increased by area 1-4-4'-1'-2'-2-1. And the heat supplied to steam increases by the area A-2'-2-B. These two areas are nearly equal; however, the net effect is to increase the thermal efficiency. This could be expected because the average temperature of heat rejection of the cycle decreases with decrease in condenser pressure.

Unit cycle analysis



Feed water heating



- Some heat transferred to feedwater from 2 to 3
- Slightly less work produced in turbine from 7 to 8
- Slightly less heat rejected in condenser from 8 to 1
- Heat added in boiler only from 4 to 6
- Closer to Carnot Cycle therefore higher efficiency
- With multiple heaters more feedwater heating
- In limit boiler adds heat only from 5 to 6
- Equal to Carnot Cycle therefore maximum efficiency.

Thank You