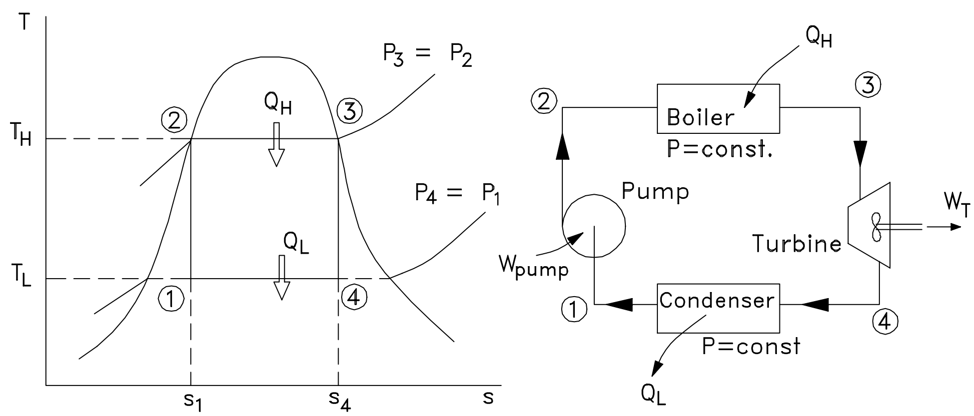
Week 4: Lecture 1

Carnot Cycle

- an ideal theoretical cycle that is the most efficient conceivable
- based on a fully reversible heat engine
- in practice the thermal efficiency of real world heat engines are about half that of the ideal Carnot cycle



Process	State Points	Description
Pump	$1 \rightarrow 2$	isentropic compression from $T_L \rightarrow T_H$ to return vapour to a liquid state
Heat Supply	$2 \rightarrow 3$	heat is supplied at constant temperature and pressure
Work Output	$3 \rightarrow 4$	the vapour expands isentropically from the high pressure and temperature to the low pressure
Condenser	$4 \rightarrow 1$	the vapour which is wet at 4 has to be cooled to state point 1

Week 4: Lecture 1

Cycle Efficiency

- defined as the net work output divided by the gross heat supplied

$$\eta = \frac{W_{net}}{Q_H} = \frac{Q_H - Q_L}{Q_H} = 1 - \frac{T_L}{T_H}$$

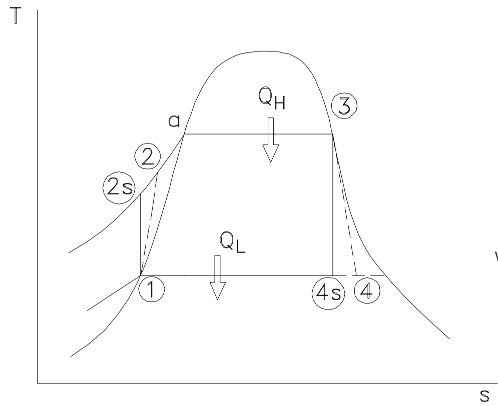
Practical Problems

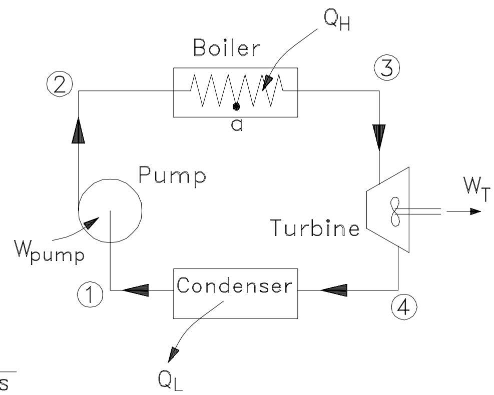
- at state point 1 the steam is wet at T_L and it is difficult to pump water/steam (two phase) to state point 2
- the pump can be sized smaller if the fluid is 100% liquid water
- the pump is smaller, cheaper and more efficient
- can we devise a Carnot cycle to operate outside the wet vapour region
  - between state points 2 and 3 the vapour must be isothermal an at different pressures - this is difficult to achieve
  - the high temperature and pressure at 2 and 3 present metallurgical limitations

The net effect is that the Carnot cycle is <u>not</u> feasible for steam power plants.

Week 4: Lecture 2

Rankine Cycle





- working fluid is alternately vaporized and condensed as it recirculates is a closed cycle
- water is typically used as the working fluid because of its low cost and relatively large value of enthalpy of vaporization
- the condensation process is allowed to proceed to completion → state point 1 - saturated liquid
- the water at state point 1 can be conveniently pumped to the boiler pressure at state point 2
- but the water is not at the saturation temperature corresponding to the boiler pressure
- heat must be added to change the water at 2 to saturated water at 'a'

Rankine Efficiency

$$\eta_R = \frac{\textit{net work output}}{\textit{heat supplied in the boiler}}$$

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

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

If the pump work is considered negligible in relation to the turbine work i.e. $(h_1 - h_2) \to 0$

Week 4: Lecture 2

Therefore

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

If the pump work is included and we consider the fluid to be incompressible

$$(h_1 - h_2) = v(P_1 - P_2)$$

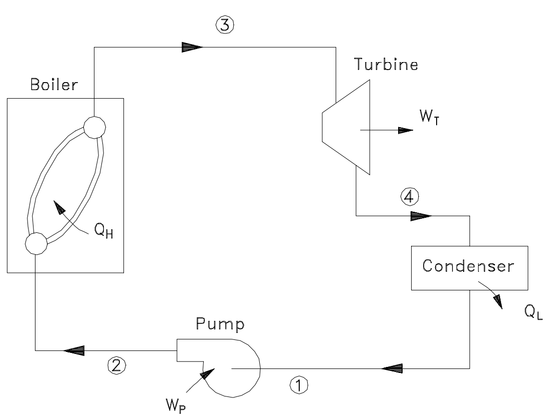
Since the actual process is irreversible, an isentropic efficiency can be defined such that

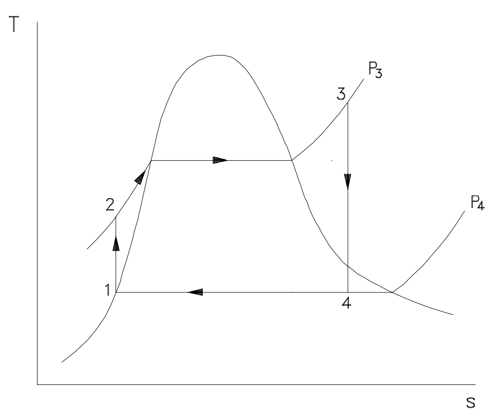
$$\text{Expansion process} \quad \Rightarrow \quad \text{Isentropic efficiency} \quad = \quad \frac{\text{actual work}}{\text{isentropic work}}$$

$$\text{Compression process} \quad \Rightarrow \quad \text{Isentropic efficiency} \quad = \quad \frac{\text{isentropic work}}{\text{actual work}}$$

Rankine Cycle with Superheat

- the average temperature at which heat is supplied in the boiler can be increased by superheating the steam
- the dry saturated steam from the boiler is passed through a second bank of smaller bore tubes within the boiler until the steam reaches the required temperature

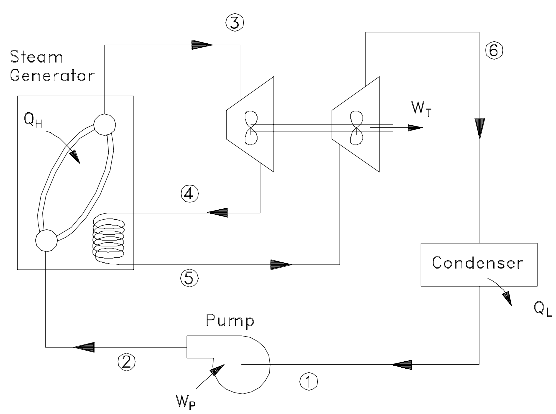


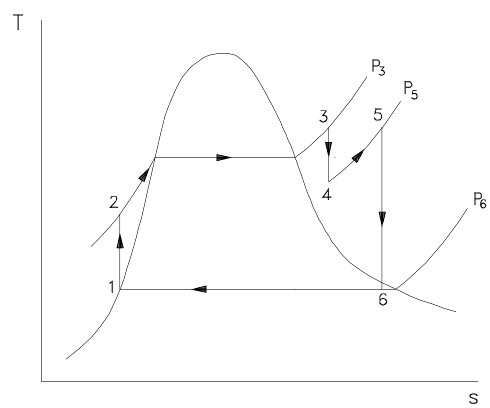


Week 4: Lecture 2

Rankine Cycle with Reheat

- the wetness at the exhaust of the turbine should be no greater that 10% - this can result in physical erosion of the turbine blades
- but high boiler pressures are required for high efficiency - tends to lead to a high wetness ratio
- to improve the exhaust steam conditions, the steam can be reheated with the expansion carried out in two steps

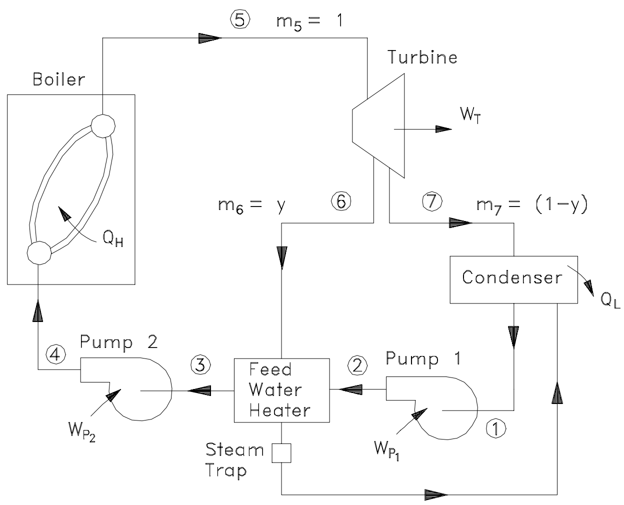


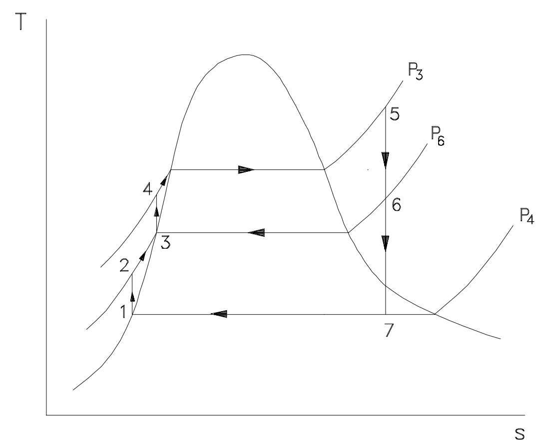


Week 4: Lecture 3

Rankine Cycle with Regeneration

- Carnot cycle has efficiency - $\eta = 1 - T_L/T_H$
  - add Q_H at as high a T_H as possible
  - reject Q_L at as low a T_L as possible
- the Rankine cycle can be used with a "Feedwater Heater" to heat the high pressure sub-cooled water at the pump exit to the saturation temperature
  - most of the heat addition (Q_H) is done at high temperature





Week 4: Lecture 3

Feedwater Heaters

1. **OPEN FWH** - streams mix → high temperature steam with low temperature water at constant pressure)
   - working fluid passes isentropically through the turbine stages and pumps
   - steam enters the first state turbine at state 1 and expands to state 2 - where a fraction of the total flow is bled off into an open feedwater heater at P_2
   - the rest of the steam expands into the second stage turbine at state point 3 - this portion of the fluid is condensed and pumped as a saturated liquid to the FWH at P_2
   - a single mixed stream exists the FWH at state point 6
2. **CLOSED FWH** - heat exchangers, streams do not mix (different pressures)
   - the incoming feedwater does not mix with the extracted steam
   - both streams flow separately through the heater
   - this allows the two streams to be at different pressures
   - a steam trap which allows only liquid to pass, is inserted in the condensed steam line, leaving the heater to insure all the extracted steam condenses before it leaves the heater
   - the condensate is then passed to the low pressure line of the condenser