Power and Refrigeration Systems – With Phase Change

(Lecture 11)

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(*) Some texts and figures are borrowed from Sonntag & Borgnakke unless noted otherwise.

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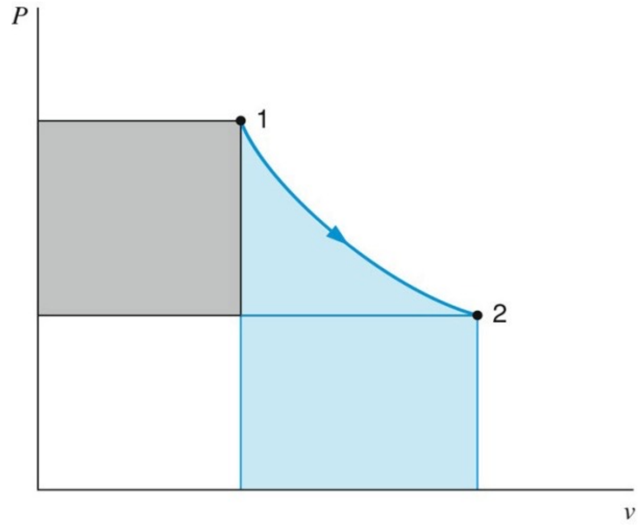
9.1 Introduction to Power Systems

- The shaft work in a reversible, steady-state process in a control volume is given as (e.g. turbine, compressor):

$$w = -\int v dP$$

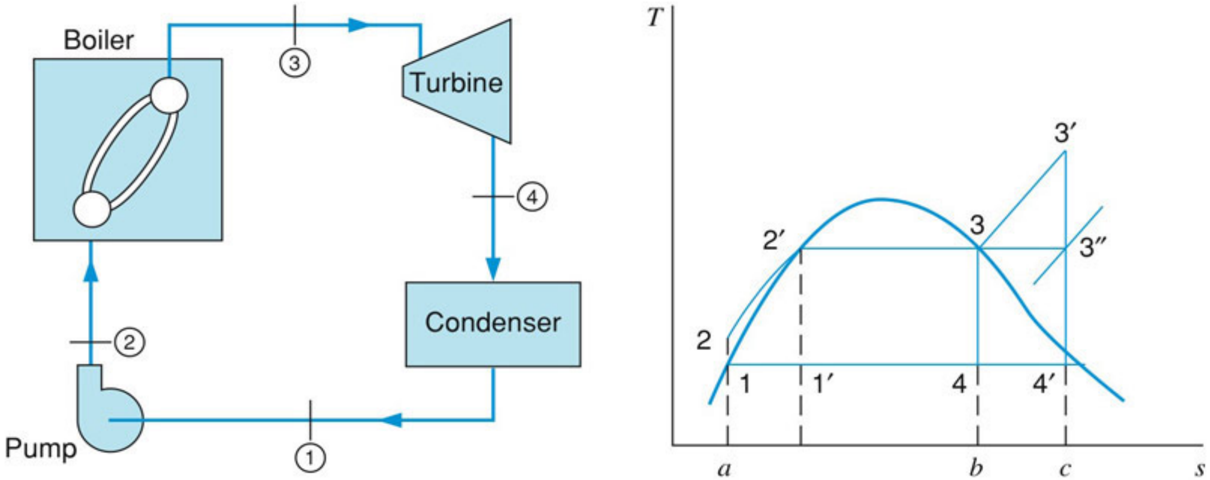


- The boundary work in a quasi-equilibrium process of a control mass is given as (e.g. internal combustion engine):

$$w = \int P dv$$

9.2 The Rankine Cycle

➔ The Rankine cycle is the ideal model for the simple steam power plant.



1 - 2 : Reversible adiabatic pumping process

2 - 3 : $P = const$*, reversible heat transfer (addition)*

3 - 4 : Reversible adiabatic expansion

4 - 1 : $P = const$*, reversible heat transfer (rejection)*

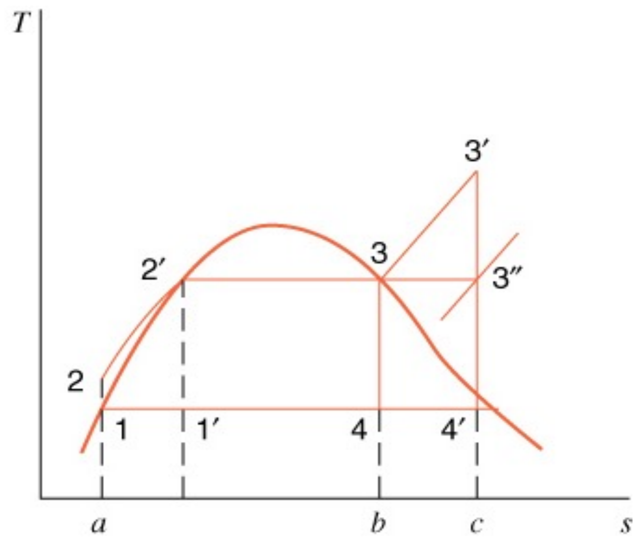
- With negligible changes of KE and PE, heat transfer and work can be shown as the areas in T-s diagram.

Considering the cycle 1-2-2'-3-4-1,

$$\eta_{th} = \frac{w_{net}}{q_H} = \frac{q_H - q_L}{q_H} = \frac{\text{area 1-2-2'-3-4-1}}{\text{area a-2-2'-3-b-a}}$$

$$\eta_{th} = 1 - \frac{|q_L|}{|q_H|} = 1 - \frac{\left|\int Tds\right|_L}{\left|\int Tds\right|_H} = 1 - \frac{T_{L,avg}\Delta S}{T_{H,avg}\Delta S}$$

$$= 1 - \frac{T_{L,avg}}{T_{H,avg}}$$

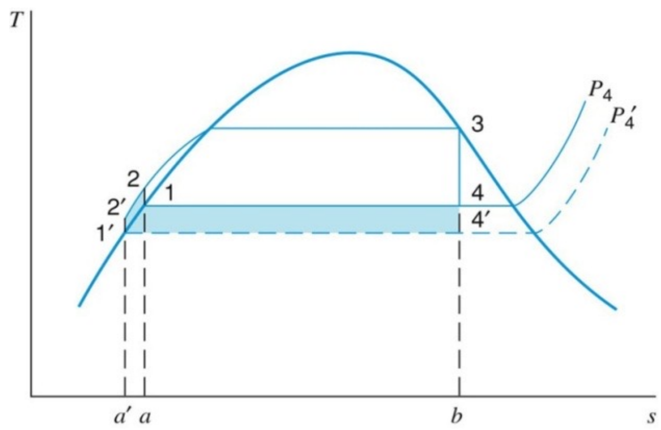


As $T_{L,avg}$ decreases or $T_{H,avg}$ increases, the cycle efficiency increases.

9.3 Effect of Pressure and Temperature on the Rankine Cycle

➔ There are several operating parameters that affect the efficiency of a simple Rankine cycle.

1. Lowering condenser pressure



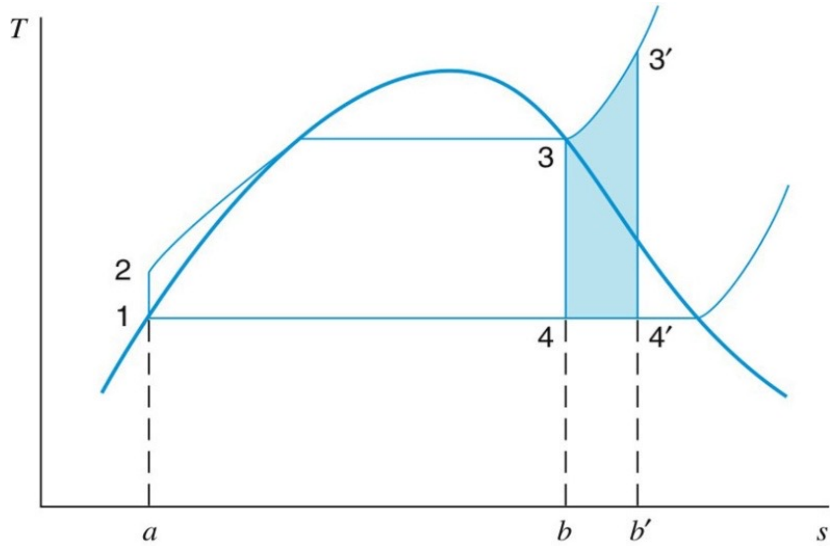
$$T_{H,avg} : slighly \downarrow \quad T_{L,avg} : \downarrow$$

$$\eta_{th} = 1 - \frac{T_{L,avg}}{T_{H,avg}} \uparrow$$

$$x \downarrow : Corrosion$$

If x < 0.9, there is a decrease in turbine efficiency and erosion of the turbine blades occurs.

2. Superheating

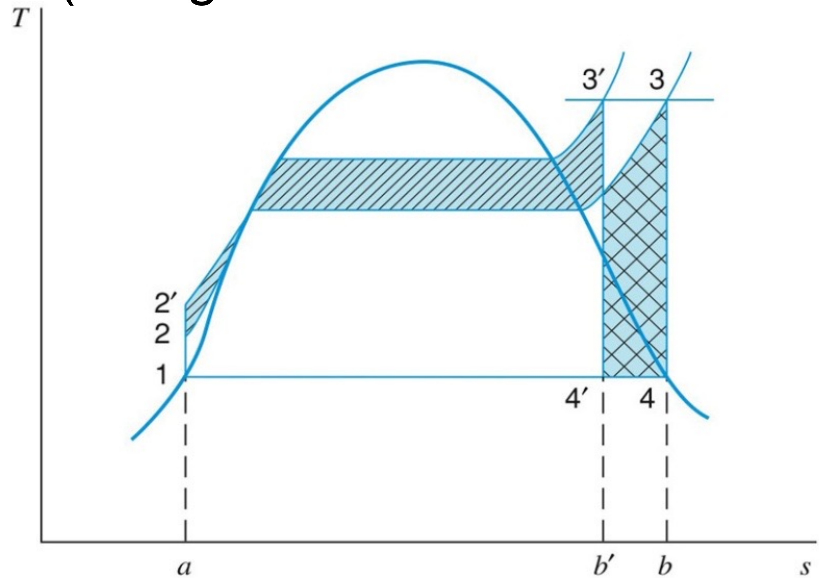


$T_{H,avg}$: ↑ $T_{L,avg} = const$

$$\eta_{th} = 1 - \frac{T_{L,avg}}{T_{H,avg}} \uparrow \qquad x \uparrow$$

There is the maximum T and P allowable for a given turbine. (Material issues)

3. Increasing the boiler pressure (at a given max. T and cond. P)

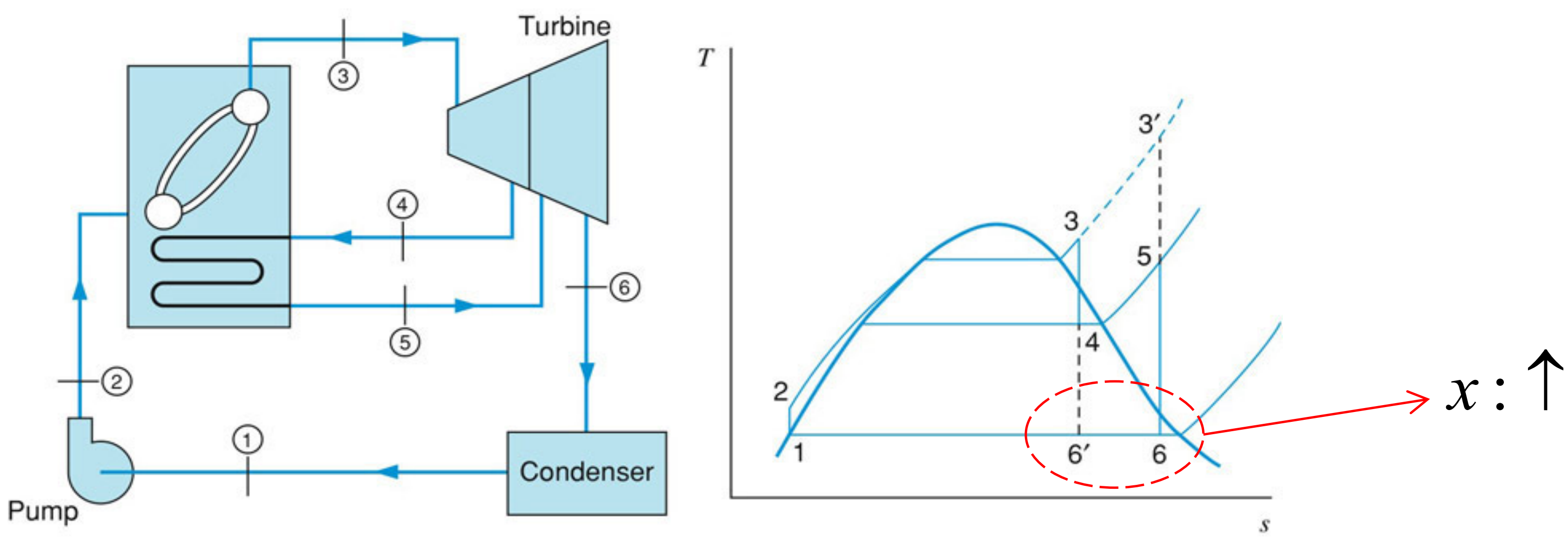


$T_{H,avg}$: ↑ $T_{L,avg} = const$

$$\eta_{th} = 1 - \frac{T_{L,avg}}{T_{H,avg}} \uparrow \qquad x \downarrow$$

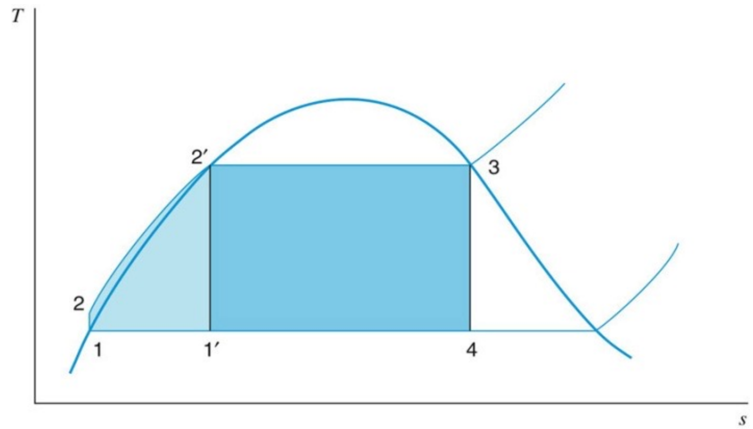
9.4 The Reheat Cycle

- To achieve higher efficiency at higher boiler pressure without excessive moisture at the exit of the turbine, reheat cycle has been developed.
  - The steam is expanded to some intermediate pressure in the turbine and is then reheated in the boiler.



9.5 The Regenerative Cycle and Feedwater Heaters

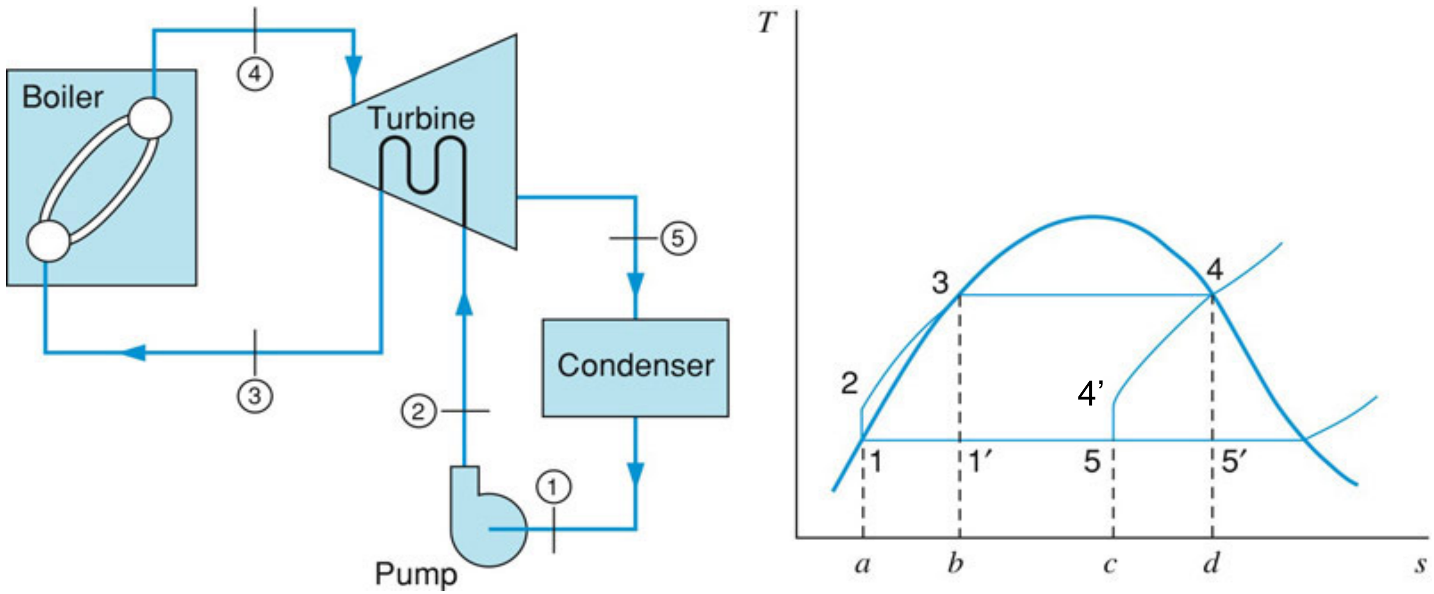
- In a typical Rankine cycle, the heat addition at lower temperatures (2-2') decreases the overall cycle efficiency.



$$\eta_{th} = 1 - \frac{T_{L,avg}}{T_{H,avg}}$$

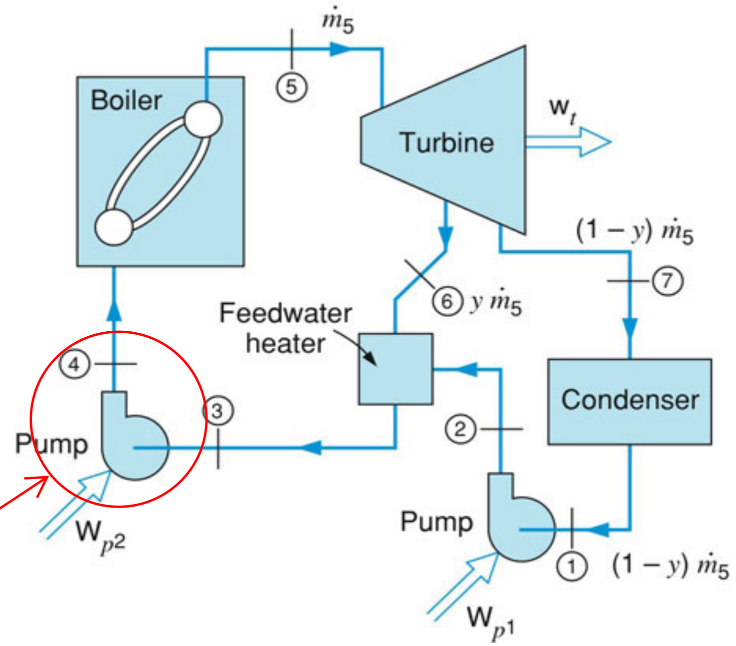
- In a regenerative cycle, the working fluid enters the boiler at some state between 2 and 2' (or at higher temperature than T_2), thus increasing the cycle efficiency.

- Consider an idealized regenerative cycle.
  - Heat addition (2→3) is performed by reversibly transferring heat from the working fluid in the turbine as it expands (4→4').
  - This cycle may achieve the Carnot cycle efficiency.

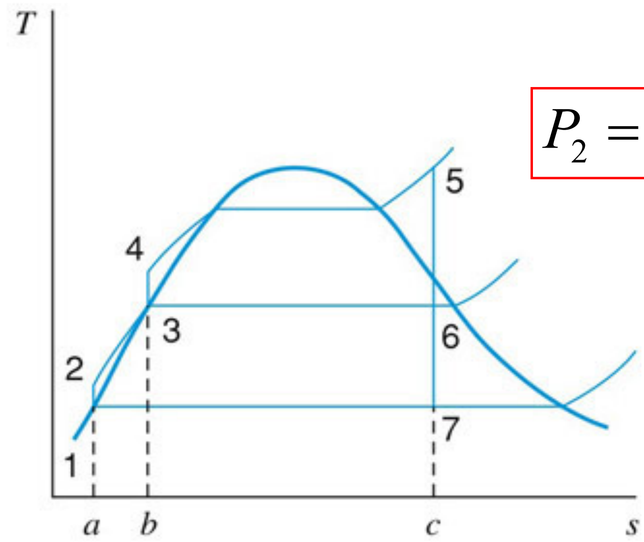


- But, this cycle is impractical to perform such a heat transfer in the turbine. Also the quality at the turbine exit (state 5) is too low.

- In practice, either an open or a closed feedwater heater (or combination of those) is applied.
- Consider an open feedwater heater:



Additional pump required



$$P_2 = P_3 = P_6$$

$$\dot{m}_2 + \dot{m}_6 = \dot{m}_3$$

$$y = \dot{m}_6/\dot{m}_5$$ *extraction fraction*

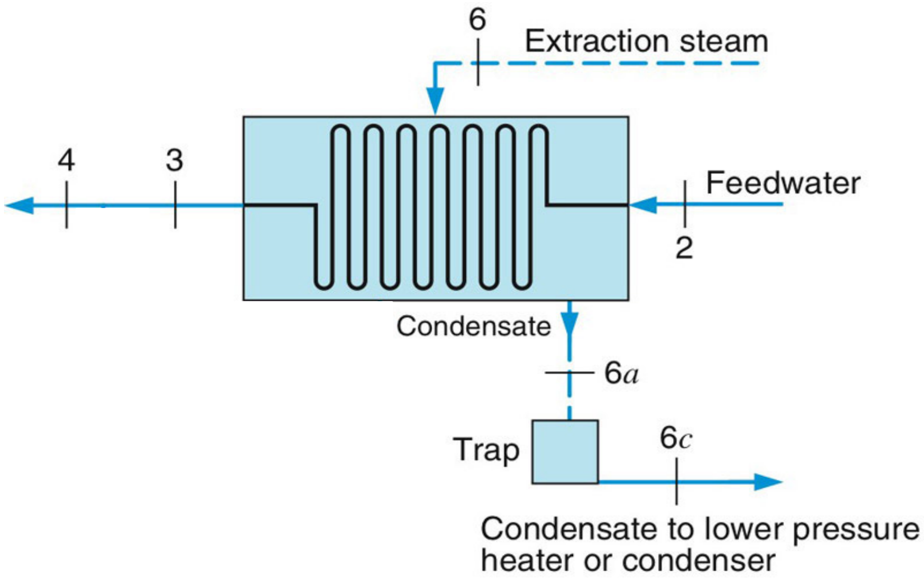
$$\dot{m}_7 = (1-y)\dot{m}_5 = \dot{m}_1 = \dot{m}_2$$

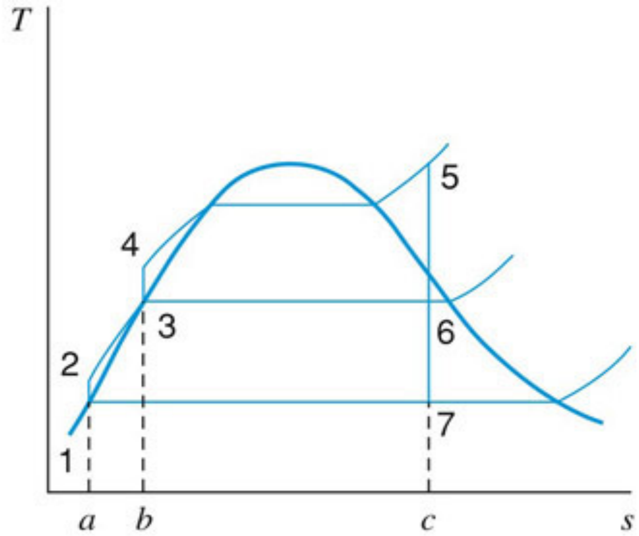
$$\dot{m}_2 h_2 + \dot{m}_6 h_6 = \dot{m}_3 h_3$$

$$(1-y)\dot{m}_5 h_2 + y\dot{m}_5 h_6 = \dot{m}_5 h_3$$

$$y = \frac{h_3 - h_2}{h_6 - h_2}$$

➔ Consider a closed feedwater heater:





$$\dot{m}_4 = \dot{m}_3 = \dot{m}_2 = \dot{m}_5; \qquad \dot{m}_6 = y\dot{m}_5 = \dot{m}_{6a} = \dot{m}_{6c}$$

$$\dot{m}_5 h_2 + y\dot{m}_5 h_6 = \dot{m}_5 h_3 + y\dot{m}_5 h_{6a}$$

$$y = \frac{h_3 - h_2}{h_6 - h_{6a}}$$

9.6 Deviation of Actual Cycles from Ideal Cycles

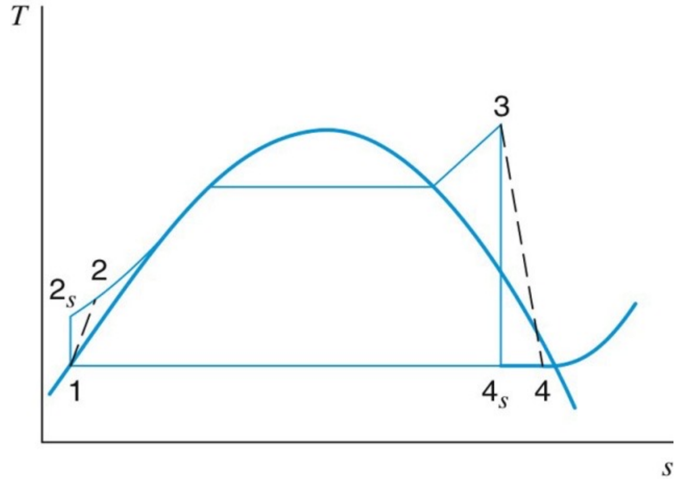
- The most important losses are due to the turbine, the pump, the pipes, and the condenser.

(Turbine and pump losses)

1. The biggest loss is associated with the flow of the working fluid through the blades and passages (frictions, throttling, etc.).
2. Heat transfer to the surroundings can be a loss but of secondary importance.

$$\eta_{\text{turbine}} = \frac{w}{w_s} = \frac{h_i - h_e}{h_i - h_{es}}$$

$$\eta_{\text{comp}} = \frac{w_s}{w} = \frac{h_i - h_{es}}{h_i - h_e}$$

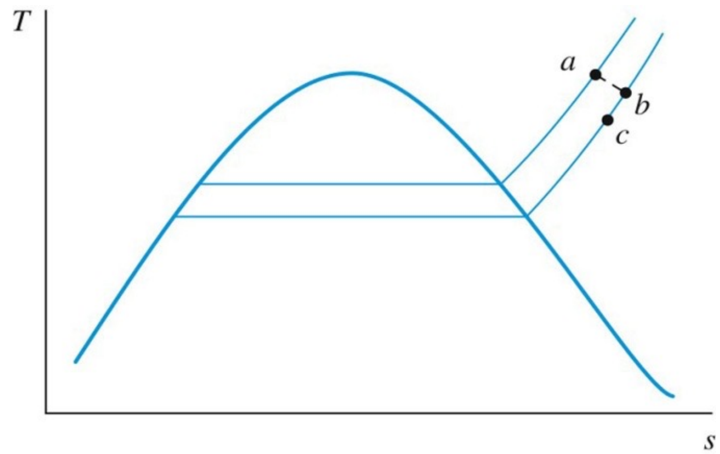


(Piping losses)

Pressure drops by frictions and heat transfer to the surroundings are the major piping losses.

$$a \rightarrow b : Pressure\ Loss$$

$$b \rightarrow c : Heat\ Transfer$$



(Condenser losses)

There can be minor losses associated with the cooling below the saturation temperature of the liquid leaving the condenser, which requires additional heat transfer to bring liquid back to its saturation temperature.

9.7 Combined Heat and Power: Other Configurations

- A typical cogeneration refers to the production of electricity and heat, thus reducing capital cost of equipment and operating costs.
- Examples include:

1. Gas turbine(GT) CHP
2. Steam turbine (ST) CHP
3. Combined Cycle (GT+ST) CHP
4. IC engine(ICE) CHP
5. Fuel-cell (typically MCFC or SOFC) CHP
6. Nuclear power plant CHP

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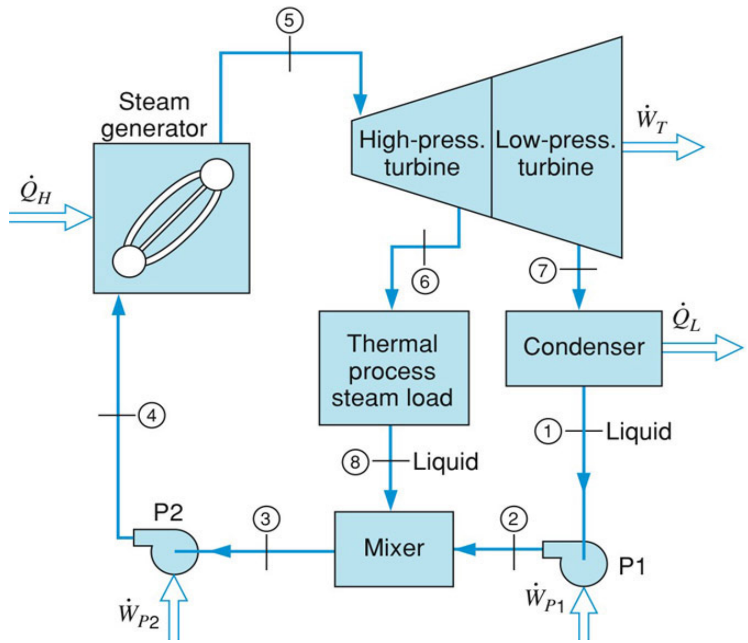
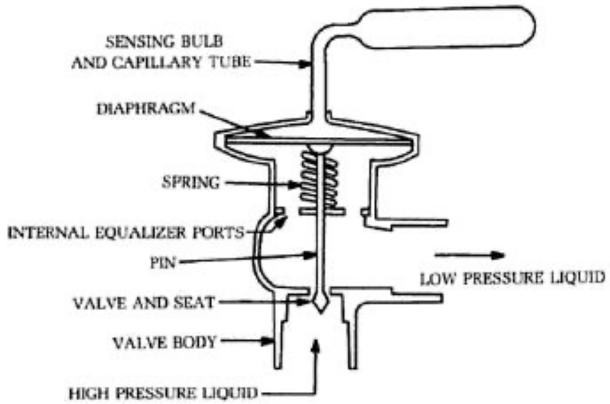


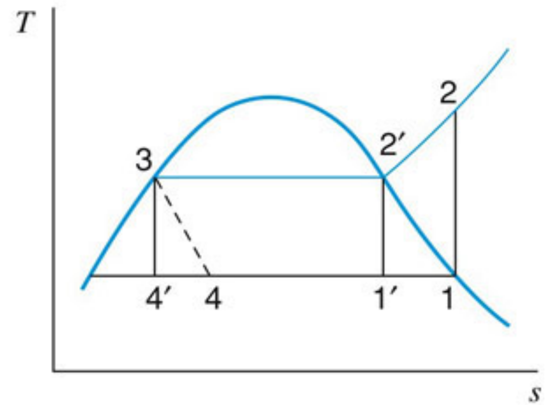
9.8 Introduction to Refrigeration Systems
9.9 The Vapor-Compression Refrigeration Cycle

- The refrigeration cycle is working in the reverse of the power cycle.
- However, the expansion process (3→4 or 4') occurs nearly at liquid phase with small specific volume(v), which produces very little work.
  - A turbine (3→4') is replaced with a throttling device (3→4).



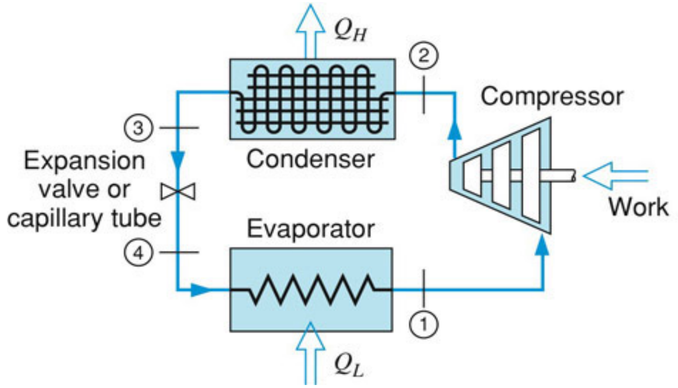
(source: www.refrigerator-troubleshooting.com)

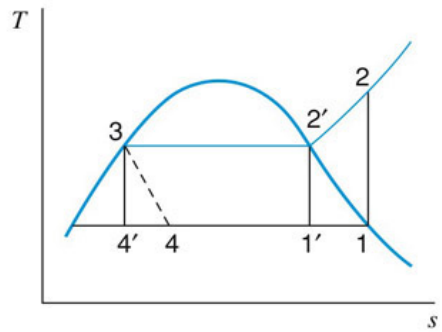
Throttle valve in a refrigerator



Vapor-compression refrigeration cycle

- The standard vapor-compression refrigeration cycle has four known processes.





①-②: *isentropic comp*

$$s_2 = s_1$$

②-③: $P = const$, *condensation*

③-④: isenthalpic expansion

$$h_4 = h_3$$

④-①: $P = const$, *evaporation*

- The system can be used for two purposes.
  - A refrigeration system maintains a low temperature T_1 relative to the ambient temperature T_3.

$$\beta(COP) = \frac{q_L}{w_c}$$

  - A heat pump system maintains a high temperature T_3 above the ambient temperature T_1.

$$\beta'(COP) = \frac{q_H}{w_c}$$

9.11 Deviation of the Actual Vapor-Compression Refrigeration Cycle from the Ideal Cycle

➔ There are several losses considered:

1. During the compression(1→2 or 2'), there are irreversibilities and heat transfer either to or from the surroundings.

2. There is some drop in pressure through the condenser (3→4) and the evaporator (7→8), mostly due to friction.

3. The refrigerant through the evaporator may be slightly superheated, which increases the pumping work with an increased specific volume.