CM 3230 Thermodynamics, Fall 2016

Lecture 10

1. Rankine Cycle (continued)

Q: How does one incorporate machine efficiencies, e.g. for turbine and compressor ?

A: For turbine,

$$\eta_{turbine} = \frac{w_{by,s}^{actual}}{w_{by,s}^{reverisble}} \quad \rightarrow \quad \hat{h}_2 = \hat{h}_1 + \eta_{turbine}\left(\hat{h}_2^{reversible} - \hat{h}_1\right) > \hat{h}_2^{reversible}$$

For compressor,

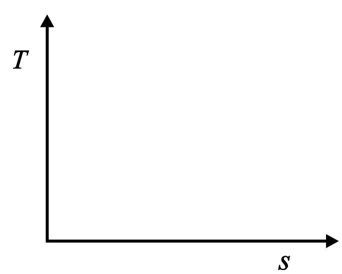
$$\eta_{comp} = \frac{w_{by,s}^{reversible}}{w_{by,s}^{actual}} \quad \rightarrow \quad \hat{h}_4 = \hat{h}_3 + \frac{\left(\hat{h}_4^{reversible} - \hat{h}_3\right)}{\eta_{comp}} > \hat{h}_4^{reversible}$$

(see example 3.15, p. 168-169)

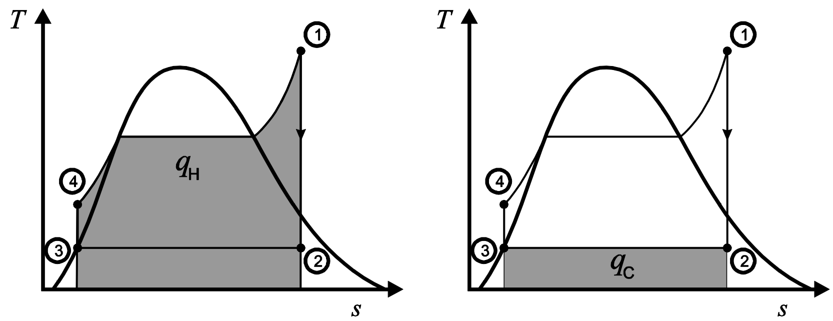
2. T-s Diagrams

- P-v diagrams focus on work by: area under curve is $w_{by}^{rev} = \int P dv$
- T-s diagrams focus on heat transferred in: area under curve is $q_{in}^{rev} = \int T\, ds$

In class exercise: draw the T-s diagram for a Carnot cycle



For Rankine cycle:



Rankine *T-s* diagram

$$w_{by,net} = q_H - q_C$$

Q: What if compressor is inefficient? What if turbine path is inefficient ?

(Note: area for w_{net} as shown in Figure 3.8 can be misleading if turbine is not isentropic)

3. Vapor Compression Refrigeration Cycle

- Contains 4 main units:

  - **Evaporator (cooling box)**
    - Refrigerant enters as liquid+vapor mix, but exits as saturated vapor
    - Pressure is chosen so that corresponding boiling point of the refrigerant is colder than item to be cooled in the box

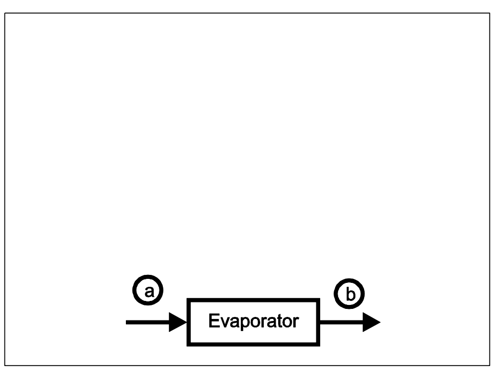
  - **Compressor**
    - Increase pressure of vaporized refrigerant
    - Ideal case: isentropic
    - Outlet pressure should be high enough so that the corresponding saturation temperature (at the condenser) is warmer than the outside temperature

- **Condenser (hot coils at the back)**
  - Often has coiled tubes attached with cooling fins to improve heat transfer rate
  - Along isobaric path, it has to first cool refrigerant down to saturation condition before condensation commense
  - Outlet condition is saturated liquid refrigerant

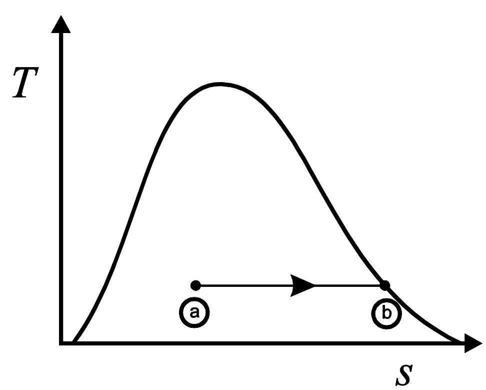
- **Throttler (valve)**
  - Isenthalpic process → adiabatic but not reversible → entropy increases
  - Enters as saturated liquid at high pressure
  - Path is inside the phase envelope
  - Outlet pressure is chosen so that refrigerant exits as a liquid+vapor mix at the temperature needed by the evaporator unit

In-class exercise:

a) Sketch equipment diagram of the vapor-compression refrigeration cycle
b) Sketch the accompanying T-s diagram of the refrigeration cycle
c) Fill-in the work/heat "balance sheet" for the paths



Refrigeration Cycle



Refrigerant *T*-*s* diagram

Work and Heat Paths "Balance Sheet" of ideal Refrigeration Cycle

Unit/Path	Shaft Work By Refrigerant	Heat Into Refrigerant
Evaporator: a→b	$\dot{W}_{by,s,a\to b} = 0$	
	Notes:	
Compressor: b→c		$\dot{Q}_{in,b\to c} = 0$
	Notes:	
Condenser: c→d		
	Notes:	
Throttle: d→a		
	Notes:	

Example 3.16 (p.171)

Given: $P_{low} = 120\ kPa, P_{high} = 900\ kPa$

Required: COP, $\dot{m}$ for $\dot{Q}_C = 10\ kW$.

Data needed:

Saturation Table:

@ P_{low} → $h_{vap}(= h_b), s_{vap}(= s_b)$

@ P_{high} → $h_{liq}(= h_d = h_a)$

Superheated Table:

@ P_{high} and s_b → h_c

Solution :

$h_a = h_d = 25.5\ kJ/mol\ ;\ \ h_b = 39.3\ kJ/mol\ ;\ h_c = 43.6\ kJ/mol$

$q_C = q_{in,a\to b} = h_b - h_a = 13.8\ kJ/mol \to\ \ \dot{n} = (10\ kW)/q_C = 0.73\ mol/s$

$$COP = \frac{q_C}{|q_C + q_H|} = \frac{13.8}{|13.8 + (h_d - h_c)|} = 3.21$$

Work and Heat Paths "Balance Sheet" of ideal Refrigeration Cycle

Unit/Path	Shaft Work By Refrigerant	Heat Into Refrigerant
Evaporator: a→b	$\dot{W}_{by,s,a\to b} = 0$	$\dot{Q}_{in,a\to b} = \dot{m}(\hat{h}_b - \hat{h}_a)$
	Notes: $\hat{h}_b = \hat{h}_v$ @ P_{low},saturated vapor	
Compressor: b→c	$\dot{W}_{by,s,1\to 2} = -\dot{m}(\hat{h}_c - \hat{h}_b)$	$\dot{Q}_{in,b\to c} = 0$
	Notes: a) saturated vapor, $P_b(= P_{low}) \xrightarrow[\text{table}]{} \hat{s}_b$ b) $\hat{s}_c = \hat{s}_b, P_c(= P_{high}) \xrightarrow[\text{table}]{} \hat{h}_c$	
Condenser: c→d	$\dot{W}_{by,s,c\to d} = 0$	$\dot{Q}_{in,c\to d} = \dot{m}(\hat{h}_d - \hat{h}_c)$
	Notes: saturated liquid, $P_d\left(= P_{high}\right) \xrightarrow[table]{} \hat{h}_d = \hat{h}_{liq}@P_{high}$	
Throttle: d→a	$\dot{W}_{by,s,d\to a} = 0$	$\dot{Q}_{in,d\to a} = 0$
	Notes: $\hat{h}_a = \hat{h}_d : \left(\hat{h}_a, P_{low}\right) \xrightarrow[\text{table}]{} x_{vap}$ (not necessary for heat calculation)	