CM 3230 Thermodynamics, Fall 2016

Lecture 9

1. Rankine Cycle (Vapor Compression Power Cycle)

- Contains 4 main units:

  - **Turbine**
    - converts enthalpy of working fluid to useful work, e.g. via generator
    - ideal case: fluid undergoes isentropic expansion
      a. outlet pressure is lower than inlet pressure
      b. adiabatic and reversible process for the fluid
    - practical constraints: want outlet stream to be saturated, possibly high quality “wet steam”

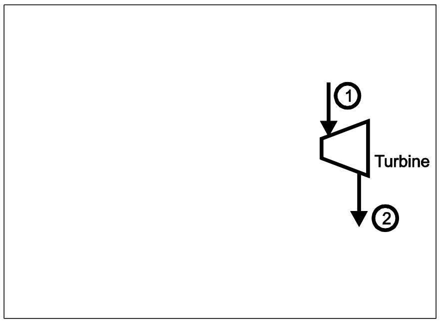
  - **Condenser**
    - Working fluid changes phase at constant pressure, i.e. inside phase envelope.
    - Ideal case: heat exchange is only between working fluid and cooling fluid (i.e. heat lost by working fluid = heat gained by cooling fluid → no heat lost to other surrounding)
    - Practical/economic issues:
      a. Since next unit downstream is a compressor, we want the outlet to be completely liquid (bubbles not good for compressor)
      b. But do not want to cool working fluid too far from saturated liquid condition
      c. Cooling needs to be fast enough for required power delivery (heat transfer rate depends on temperature difference, etc. → transport problem)

- **Compressor**
  - Increase the inlet pressure to a much higher outlet pressure
  - Ideal case: isentropic (adiabatic and reversible path for the working fluid)
  - Practical issues
    a. Work done by compressor should be much less than work given to turbine (→ In some designs, part of the work delivered by the turbine is used to run compressor.)
    b. But want outlet pressure high to make the boiler temperature higher (recall conclusion of efficiency of ideal Carnot cycles)

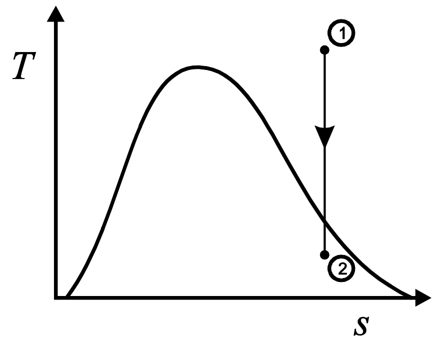
- **Boiler**
  - Takes compressed working liquid and boils (isobarically, at high pressure) it to superheated condition
  - Ideal case: heat gained by working fluid = heat delivered by “fuel source” → no heat lost to other surrounding
  - Practical issue: the outlet temperature, together with the fixed pressure, has to be at the point such that when the turbine path is accomplished, the working fluid is a high quality steam.
  - Fuel sources: combustion, nuclear reaction, others (solar?)
  - Boiling rates needs to be fast enough for required power delivery (heat source depends on heat transfer and reaction rates, etc. → transport and kinetics problem)

In class exercise:

a) Sketch the equipment diagram of the Rankine cycle (and label the points in the path)
b) Sketch the accompanying T-s diagram of ideal Rankine cycle
c) Fill-in the work/heat “balance sheet” for the paths



Rankine Engine



Rankine *T*-*s* diagram

Work and Heat Paths “Balance Sheet” of ideal Rankine Cycle

Unit/Path	Shaft Work By Fluid	Heat Into Fluid
Turbine: 1→2		$\dot{Q}_{in,1\rightarrow 2} = 0$
	Notes:	
Condenser: 2→3	$\dot{W}_{by,s,2\rightarrow 3} = 0$	
	Notes:	
Compressor: 3→4		
	Notes:	
Boiler: 4→1		
	Notes:	

Example 3.14. Rankine Engine Cycle

Given : $T_1 = 600°C, P_1 = 10\ MPa, P_2 = 100\ kPa$

Required: $\dot{\hat{w}}_{by,s,net}$, η_{engine}, compare with Carnot efficiency

Solution:

Need:

$$\hat{h}_1 = (\qquad\qquad)\frac{kJ}{kg}$$

$$\hat{h}_2 = (\qquad\qquad)\frac{kJ}{kg}$$

$$\hat{h}_3 = (\qquad\qquad)\frac{kJ}{kg}$$

$$\hat{h}_4 = (\qquad\qquad)\frac{kJ}{kg}$$

Then

$$\hat{w}_{by,s,net} = (\hat{h}_1 - \hat{h}_2) + (\hat{h}_3 - \hat{h}_4) = (\qquad\quad)\frac{kJ}{kg}$$

$$\eta_{engine} = \frac{\dot{\hat{w}}_{by,s,net}}{\dot{q}_{in,4\to1}} = \frac{\dot{\hat{w}}_{by,s,net}}{\hat{h}_1 - \hat{h}_4} = (\qquad)$$

For Carnot efficiency: $T_H = T_1 = 600°C$ and $T_C = (\qquad)°C$.

$$\eta_{carnot} = \frac{T_H - T_C}{T_H} =$$

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

<table>
<tr><th>Unit/Path</th><th>Shaft Work By Fluid</th><th>Heat Into Fluid</th></tr>
<tr><td rowspan="2">Turbine: 1→2</td><td>$\dot{W}_{by,s,1\to 2} = \dot{m}(\hat{h}_1 - \hat{h}_2)$</td><td>$\dot{Q}_{in,1\to 2} = 0$</td></tr>
<tr><td colspan="2">Notes: a) $(T_1, P_1) \xrightarrow[\text{steam table}]{} (\hat{h}_1, \hat{s}_1)$
b) $(\hat{s}_2 = \hat{s}_1, P_2) \xrightarrow[\text{steam table}]{} (\hat{h}_{v,2}, \hat{h}_{l,2}, x) \to \hat{h}_2$</td></tr>
<tr><td rowspan="2">Condenser: 2→3</td><td>$\dot{W}_{by,s,2\to 3} = 0$</td><td>$\dot{Q}_{in,2\to 3} = \dot{m}(\hat{h}_3 - \hat{h}_2)$</td></tr>
<tr><td colspan="2">Notes: $\hat{h}_3 = \hat{h}_{l,2}$ (or less if excess cooling occurs)</td></tr>
<tr><td rowspan="2">Compressor: 3→4</td><td>$\dot{W}_{by,s,3\to 4} = \dot{m}(\hat{h}_3 - \hat{h}_4)$</td><td>$\dot{Q}_{in,3\to 4} = 0$</td></tr>
<tr><td colspan="2">Notes: $\hat{h}_4$ can be obtained from subcooled table, or
$\hat{h}_4 \approx \hat{h}_3 + \hat{v}_{l,3}(P_4 - P_3)$</td></tr>
<tr><td rowspan="2">Boiler: 4→1</td><td>$\dot{W}_{by,s,4\to 1} = 0$</td><td>$\dot{Q}_{in,4\to 1} = \dot{m}(\hat{h}_1 - \hat{h}_4)$</td></tr>
<tr><td colspan="2"></td></tr>
</table>