Outline

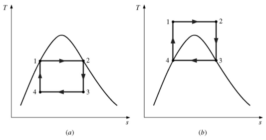
- Vapor power cycles
- Carnot vs. Rankine
- Ideal vs. actual

Vapor power cycles

- Vapor power cycle – working fluid is alternatively vaporized and condensed
- Steam is most common working fluid (low cost, availability, high enthalpy of vaporization)
- Heat source either coal, nuclear, or NG
- Steam goes through same cycle for all

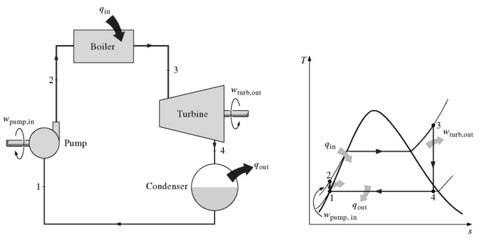
Carnot cycle as ideal vapor power cycle?

- Carnot most efficient between two T limits
- Under wet dome 1-2, 3-4 feasible in boiler and condenser
- T<Tcr; limits efficiency
- Isentropic expansion in turbine - but high moisture content is concern
- Isentropic compression involves two-phase to SL
- Two-phase compressor hard; hard to stop at SL
- Other options also difficult (high pressure compression and isothermal heat transfer in single-phase



Ideal Vapor Power Cycle (VPC) – Rankine Cycle

- Superheat steam in boiler; condense completely in condenser



Note: Text defines *ideal* with state 3 as SV

Ideal Rankine cycle processes

- Internally reversible; four processes
- 1-2: Isentropic compression in a pump
- 2-3: Constant pressure heat addition in a boiler
- 3-4: Isentropic expansion in a turbine
- 4-1: Constant pressure heat rejection in a condenser
- Water enters pump as SL at 1; enters boiler as CL at 2; leaves as SHV at 3; high x SLVM enters condenser

Animations

http://thermofluids.sdsu.edu/

Ideal Ranking cycle analysis

- CV around each component
- Work and heat magnitudes
- Can you derive energy balances?
- Recall working fluid is steam, so do not use ideal gas relations!!!

$$q - w = \Delta h \ (kJ/kg) \text{ for each process}$$

$$(q_{in} - q_{out}) - (w_{out} - w_{in}) = h_{inlet} - h_{outlet}$$

$$Pump(q=0): w_{pump,in} = h_2 - h_1 = v(P_2 - P_1)$$

$$h_1 = h_{f @ P_1}; v \cong v_1 = v_{f @ P_1}$$

$$Boiler(w=0): q_{in} = h_3 - h_2$$

$$Turbine(q=0): w_{turb,out} = h_3 - h_4$$

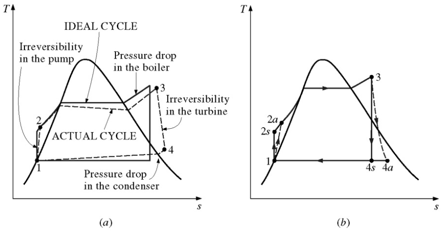
$$Condenser(w=0): q_{out} = h_4 - h_1$$

$$\therefore \eta_{th} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$

$$w_{net} = q_{in} - q_{out} = w_{turb,out} - w_{pump,in}$$

Deviation of actual vapor power cycle from idealized ones

- Frictional pressure drop and heat loss introduce irreversibilities



- Account for via isentropic efficiencies in pump and turbine

Examples

- To be done in class

Outline

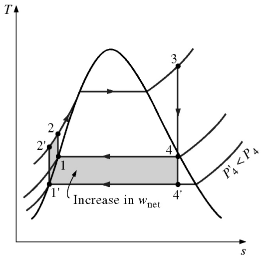
- Increasing Rankine cycle efficiency
- Examples

Increasing Rankine cycle efficiency

- Average temperature should be as high as possible during heat addition and as low as possible during heat rejection – Carnot theory
- How to achieve this?
  - Lowering condenser pressure
  - Superheating steam to high temperatures
  - Increasing boiler pressure
- Keep in mind area enclosed by cycle on T-s or P-v diagram represents net work/heat for internally reversible cycles

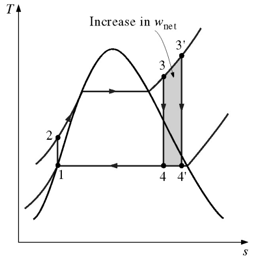
Lowering condenser pressure

- This lowers steam temperature during heat rejection
- More work input to pump and heat input, but more work output from turbine
- Overall efficiency increases due to lowering temperature during heat rejection
- Limited by saturation pressure for temperature of cooling medium; watch for air leakage; higher moisture content in turbine



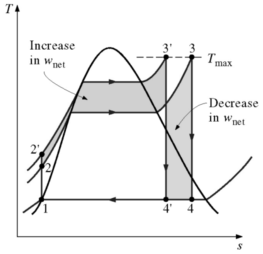
Superheating steam to high temperatures

- Increase in net work and heat input
- Overall effect is increase in efficiency due to higher T during heat addition
- Helps by decreasing moisture content in turbine
- Limited by turbine blade material (620C or 1150F); ceramics



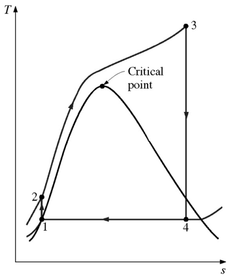
Increasing boiler pressure

- Increases average T during heat addition
- Consider fixed turbine inlet temperature
- Moisture content increases (reheat)
- 2.7MPa (400psia) in 1922 to over 30MPa (4500psia) today producing >1000MW

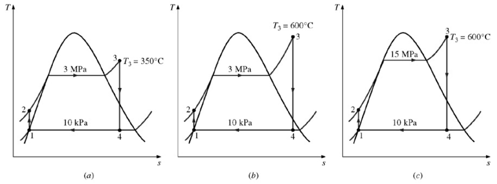


Supercritical power plant

- P>22.09MPa leads to 40/34% efficiencies for fossil/nuclear power plants
- U.S. has 112 nuclear power plants producing 21% nation’s electricity
- France – 75% nuclear

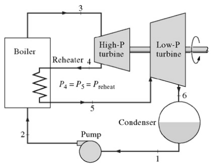


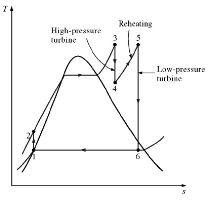
Example



Ideal reheat cycle

- How can we take advantage of increased efficiencies at higher boiler pressures without facing problem of excessive moisture at final stages of turbine?
  - Superheat steam to very high temperatures (metal limits)
  - Expand steam in stages with reheat in-between





Example

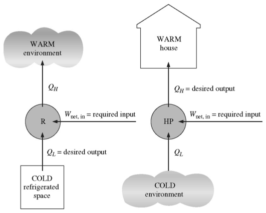
- To be done in class

Outline

- Refrigeration cycles
- Vapor compression refrigeration cycle

Objective of refrigerator/heat pump

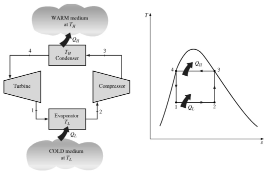
- Refrigerators
- Refrigerants
- Heat pump
- COP
- Cooling capacity is rate of heat removal from refrigerated space
- Measured in tons (1 ton (2000lbm) of liquid water at 0C into ice at 0C in 24h is 1 ton cooling capacity)
- 1 ton of refrigeration is 211kJ/min or 200Btu/min



(*a*) Refrigerator (*b*) Heat pump

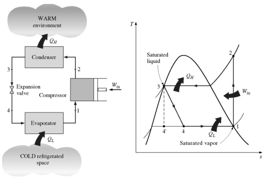
Carnot cycle as ideal cycle?

- Reversed Carnot cycle as ideal
- Gives max COP between T limits
- 1-2, 3-4 ok
- 2-3 hard to compress SLVM
- 4-1 expansion of high-moisture content refrigerant



Ideal vapor compression refrigeration (VCR) cycle

- Vaporize refrigerant completely before compression
- Replace turbine with throttling device (expansion valve or capillary tube)
- Gives ideal VCR cycle

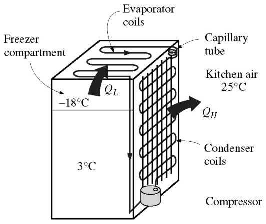


Ideal VCR cycle processes

- 1-2: Isentropic compression in compressor
- 2-3: Constant-pressure heat rejection in a condenser
- 3-4: Throttling in an expansion device
- 4-1: Constant-pressure heat absorption in evaporator
- WF enters compressor as SV at 1; exits at higher T than surrounding medium; enters condenser as SHV at 2 and leaves as SL at 3 due to heat rejection to surroundings, etc.

Household refrigerator

- Tubes in freezer compartment where heat is absorbed by refrigerant serve as evaporator
- Coils behind where heat is dissipated to surrounding air serve as condenser

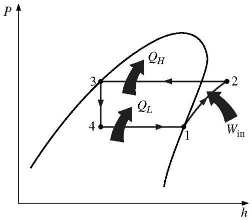


Property diagrams

- 3 of 4 processes are straight lines
- Why?
- Is ideal VCR cycle internally reversible?

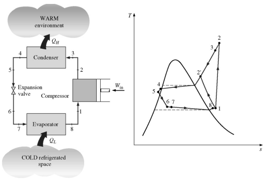
$$\left(q_{in} - q_{out}\right) - \left(w_{out} - w_{in}\right) = h_{inlet} - h_{outlet}$$

$$COP_R = \frac{q_L}{w_{net,in}} = \frac{h_1 - h_4}{h_2 - h_1}$$



Actual VCR cycle

- SH at compressor inlet
- Pressure drops in lines
- Entropy may increase or decrease in compressor due to heat loss
- Subcool liquid before entering throttling valve (increase cooling capacity)



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- Examples