8.21 Lecture 12

Phase Change Energy Conversion II

October 5, 2009
• Use what we learned @ change of phase on Wednesday to build workhorse devices today.
• The vapor compression cycle: heat pumps, refrigeration, air conditioners
• The Rankine steam cycle and steam turbines
• Some implementations of the Rankine cycle
• Marks end of Part I of the course on the “Uses of Energy”. Wednesday begins Part II on “Energy Sources”
Reminder: Thermodynamics of phase change:

- Saturated liquid, quality = 0
- Mixed phase
- Saturated vapor, quality = 1
- Saturated liquid, quality = 0
Let’s build a vapor-compression cycle air conditioner

So now let’s combine cycle analysis with our new knowledge of the thermodynamics of a fluid that can change phase.

Environments and Cycle Steps

★ First step: From liquid rich mixed phase to vapor rich mixed phase at low temperature and pressure, \( T_L \) and \( P_L \).  
**EVAPORATOR**

★ Second step: Compression from vapor rich mixed phase at \((T_L, P_L)\) to pure vapor at \((T_H, P_H)\).  
**COMPRESSOR**

★ Third step: From pure vapor at \((T_H, P_H)\) to pure liquid still at high temperature and pressure, \((T_H, P_H)\).  
**CONDENSER**

★ Fourth step: Free expansion from \((T_H, P_H)\) to \((T_L, P_L)\).  
**THROTTLE**
Step  [12]  iso-entropic (adiabatic) compression

- Enter cycle at \( 1 \)

\( T_L \) and \( P_L \) in mixed phase, mostly vapor (high quality).

- Compress keeping heat exchange with surroundings to a minimum

- Do work on fluid, but allow no heat transfer \( \Rightarrow \) enthalpy of fluid increases:

  **Must increase quality** (change liquid to vapor)

- Result: hot, high pressure, saturated vapor at \( 2 \).

  - \( W_{12} \) done on fluid
  - \( Q_{12} = 0 \)

- **Compressor** is placed in warm zone (eg. outside refrigerator or home living space)

\[
\begin{align*}
  dH &= dU + pdV + Vdp \\
  dQ &= dU + pdV = 0 \quad \text{So,} \\
  dH &= Vdp \\
  \Delta H &= \int_{P_L}^{P_H} dp \, V > 0
\end{align*}
\]
Step [23] isothermal condensation

- Start at ②

Saturated vapor at $T_H$ and $P_H$

- Allow vapor to condense by ejecting heat to high temperature environment.

- Enthalpy (heat) escapes and saturated vapor condenses to saturated liquid.

- Superficially similar to isothermal compression of Carnot cycle, but here no work is done.

- Result: Hot, high pressure saturated liquid ③.
  $\star W_{23} = 0$
  $\star Q_{23} = Q_H$

- Condensor is placed in warm zone (e.g. outside refrigerator or home living space) $T_H$ exceeds temperature of hot environment
Novel!

Step \([34]\) iso-enthalpic expansion

- Start at \(3\) Saturated liquid at \(T_H\) and \(P_H\)
- Allow liquid to expand through a \textit{throttle} into a low pressure region
- Entropy grows and temperature drops.
- Look at \(TS\)-plane: \((T \downarrow) \& (S \uparrow) \Rightarrow \text{liquid} \rightarrow \text{vapor}\)
- Result: Cold, low pressure mixed phase, of low quality — liquid rich, at point \(4\).
  
  \[\star \Delta H_{34} = 0\]
  \[\star Q_{34} = 0\]
Expansion of saturated liquid through a nozzle

- Pressure decreases and volume increases.
- Starting point I at saturation
  Moves into mixed phase at II
- Trace in ST diagram
  Remember $\Delta S > 0$.
  Temperature must decrease
  Quality (fraction of vapor) must increase
Step [41] isothermal evaporation

- Start at ④

Liquid rich mixed phase at $T_L$ and $P_L$

- Allow liquid to evaporate, extracting heat from the low temperature environment.
  
  $W_{41} = 0$
  
  $Q_{41} = Q_L$

- Result: Cold, low pressure mixed phase, of now of high quality — vapor rich, at point ①.

Summarizing energy flow

- Work done only in compressor: $W_{[12]}$
- Heat removed from low $T$: $Q_{[41]}$
- Heat ejected to high $T$: $Q_{[23]}$

$$\text{CoP}_{\text{air conditioner}} = \frac{Q_{[41]}}{W_{[12]}} \quad \text{CoP}_{\text{heat pump}} = \frac{Q_{[23]}}{W_{[12]}}$$

$T_L$ is below temperature of hot environment
Entropy

- All steps were reversible, except for small irreversibility during throttling, so coefficient of performance cannot quite reach Carnot limit

Mechanical components

Throttling valve

Condenser

Evaporator

Compressor
A scroll compressor

Same principle as throttle

Hair spray image removed due to copyright restrictions.

Please see:
http://www.grainprocessing.com/images/Hair%20Spray.jpg

A screw-type compressor

Condenser for refrigerator

Condenser image removed due to copyright restrictions.

Please see:
http://img.alibaba.com/photo/11160583/Condenser_For_Refrigerator_Water_Coolers.jpg

Evaporator for air conditioner

Evaporator image removed due to copyright restrictions.

Please see:
http://img.diytrade.com/cdimg/520742/3323685/0/1173261417/A_C_Evaporator.jpg
A quasi-realistic implementation of
The Ideal Vapor Compression Cycle

Performance

- $\Delta W_{[12]} = 17.73 \text{ kJ/kg}$
- $\Delta Q_{[41]} = 138.13 \text{ kJ/kg}$
- $\text{CoP} = \frac{138.13}{17.73} = 7.79$
- 5 tons cooling (?) = 17.5 kW
- $\dot{m} = 0.126 \text{ kg/sec}$ and $P_{\text{electric}} = 2.25 \text{ kW}$

Only the beginning of an engineering design iteration...
A more realistic vapor compression cycle

★ Many small items: frictional losses in pipes, thermal losses in compressor and throttle.

★ Temperatures of hot and cold spaces must exceed set points of cycle in order to get efficient heat transfer

★ But one significant design issue

Compressor cannot handle mixed phase without mechanical damage

★ Modify cycle so compressor works entirely in “superheated” vapor phase.
• Why this now?
• Thermodynamics of heat extraction
• Phase change in pure substances
• The vapor compression cycle: heat pumps, refrigeration, air conditioners

• The Rankine steam cycle and steam turbines
• Some implementations of the Rankine cycle
Steam Engines! Parallels
history of Industrial
Revolution

At the heart of energy consumption revolution of 1800’s

★ Heron of Alexandria circa 1st century AD

★ Thomas Newcomen (British 17th c), James Watt (British 18th c), developed reciprocating (pistons and cylinders, etc.) steam engines.

★ Charles Parsons (also British, 19th-20th c), developed steam turbine, using Rankine Cycle, which revolutionized power generation.

Steam engine images removed due to copyright restrictions.
Rankine Cycle:
Conceptually, vapor compression cooling cycle run backward

Environments and Cycle Steps

First step: Mixed fluid of low quality (exhausted) at \((T_L, P_L)\) is compressed to pure liquid (zero quality) at \((T_H, P_H)\).

Second step: Pure liquid at \((T_H, P_H)\) absorbs heat and converts to pure vapor at \((T_H, P_H)\).

Third step: Pure vapor at \((T_H, P_H)\) expands adiabatically (doing work) to mixed phase of high quality at \((T_L, P_L)\).

Fourth step: Mixed phase of high quality at \((T_L, P_L)\) expels heat and converts to mixed phase of low quality at \((T_L, P_L)\).
Step [12] iso-entropic (adiabatic) compression

- Enter cycle at ①
  
  \( T_L \) and \( P_L \) in mixed phase, mostly water (low quality).

- Compress keeping heat exchange with surroundings to a minimum

- Do work on fluid, but allow no heat transfer \( \Rightarrow \) enthalpy of fluid increases.

- Result: hot, high pressure, saturated liquid at ②.
  
  \( \star \ W_{12} = W_{\text{pump}} \text{ done on fluid} \)
  \( \star \ Q_{12} = 0 \)

- Pump
Step [23] isothermal vaporization (boiling)

- Start at \( \bullet \)
  
  Saturated liquid at \( T_H \) and \( P_H \)

- Add heat in combustion chamber/boiler

- Enthalpy (heat) converts liquid water to steam at constant temperature and pressure

- Superficially similar to isothermal expansion of Carnot cycle, but here no work is done.

- Result: Hot, high pressure saturated vapor \( \circ \).
  
  \[ W_{23} = 0 \]
  
  \[ Q_{23} = Q_H \]
Novel!

Step [34] isoentropic expansion through turbine

- Start at 3 High energy density vapor at $T_H$ and $P_H$
- Force steam to do work against blades of a turbine
- Minimize heat exchange, $\Delta S \approx 0$
- Temperature, pressure and quality all drop

- Result: Cooler, low pressure mixed phase, though still of high quality — vapor rich, at point 4.
  - $W_{34} = W_{\text{useful}}$
  - $Q_{34} = 0$
Step [41] isothermal condensation

- Start at ④

Vapor rich mixed phase at $T_L$ and $P_L$

- Allow steam to condense, expelling heat to environment.
  - $W_{41} = 0$
  - $Q_{41} = Q_L$

- Result: Cold, low pressure mixed phase, of now of low quality — liquid water rich, at point ①.

Summarizing energy flow

- Net work: $W_{[34]} - W_{[12]}$
  
  Turbine – pump
  
  - Heat take from high $T$: $Q_{[23]}$
  
  Heat ejected to low $T$: $Q_{[41]}$

$$\text{CoP} = \frac{W_{[34]} - W_{[12]}}{Q_{[23]}}$$
Mechanical components in Rankine Steam Cycle

- **Boiler**
  - \( Q_H \)\( Q_H \)

- **Pump**
  - \( W_p \)

- **Condenser**
  - \( Q_L \)\( Q_L \)

- **Turbine**
  - \( W_T \)
Steam turbine images removed due to copyright restrictions.

Please see:
http://nlcs.k12.in.us/oljrhi/brown/power/images/steamturbine.jpg
Important design considerations and a more realistic Rankine Cycle

star I Pumps

Real pumps are single phase devices, for pressurizing liquids.

Much easier to pressurize a liquid than a gas

So must be moved to saturation

Forces massive condensation systems

Image from http://commons.wikimedia.org/wiki/File:Drax_cooling_tower.jpg
Important design considerations and a more realistic Rankine Cycle

- **II Pumps**
  
  Pumps do little work on a liquid \( (dW = p\,dV) \)
  
  So they do not increase the temperature much
  
  So ② must be moved to lower temperature

- **III Turbines**
  
  High performance turbines cannot tolerate a mixed phase
  
  Droplets of liquid damage rotors and quickly degrade performance
  
  Vapor input to turbine must be superheated
  
  And fluid at outlet must be \( \gtrsim 99\% \) vapor
Realistic Rankine Cycle and its (less than optimal) consequences!

★ Latent heat of condensation is not used to power turbine.

★ Fluid at output of turbine is saturated, or even superheated, steam, with considerable untapped energy content

★ Which must be converted to liquid before it can be cycled through pumps

★ Either
  
  ● Waste all that energy up the cooling tower
  
  ● Use it for space heating: **cogeneration**!

  That is: Use the steam for space heating!
Improving the Rankine Cycle

- Use higher temperature and pressure
- Must keep turbine out of mixed phase
- Must not let $T_H$ exceed $\sim 550 - 600^\circ C$
- **Solution: Two turbines with reheating!**
Rankine Cycle with **Regeneration**

Rankine with regeneration:

- Commonly used in actual power plants
- Two turbines in series
  - Condensed subcooled liquid at ②
  - Mixed with steam tapped at ④
  - To preheat to saturated liquid at ⑦
More complex Rankine cycles

**Rankine with reheating:**
- Two turbines in series
- Output from one at \(4\)
- Re-enters boiler without recompression
- Hence no decrease in entropy before reheating
- And then to second turbine

**Rankine with regeneration:**
- Commonly used in actual power plants
- Two turbines in series
- Condensed subcooled liquid at \(2\)
- Mixed with steam tapped at \(4\)
- To preheat to saturated liquid at \(7\)
Brayton-Rankine combined cycles
Brayton Gas Turbine Cycles

Open cycle gas fired turbine

★ What’s the idea? Burn natural gas to produce high $T$ and high $P$ vapor

Directly powers turbine

★ Very high temperatures $\sim 1200^\circ C$ and efficiencies $\sim 35 - 42\%$.

★ Elements in cycle

- [12] Fresh air enters compressor: Adiabatic compression
- [23] Combustion: Isobaric heating
- [34] Turbine: Adiabatic expansion
- [41] Exhaust: Isobaric cooling
Brayton Gas Turbine Cycles

Combine Brayton Gas Cycle with Rankine Steam Cycle

- Very high temperatures
  \( \sim 1200^\circ\text{C} \) and efficiencies
  \( \sim 35 - 42\% \).

- By-product gases from gas turbine are hot enough,
  \( \sim 500^\circ\text{C} \) to source a downstream Rankine cycle

- Ideally combine with cogeneration for most greatest efficiency!

- Efficiencies exceed 60 – 65 % compared to 30-40 % for separate Rankine or Brayton cycles (when using natural gas)
Gas Turbine Combined Cycles

Combine Brayton Gas Cycle with Rankine Steam Cycle

★ Ideally run with natural gas
★ Can use syngas from coal gasification. But larger carbon footprint
★ Other ideas include integrated solar combined cycle
Rankine cycles in other applications

- **Solar thermal energy conversion**
- **Ocean thermal energy conversion**

Using ammonia or other fluid with appropriate thermodynamics

- **Low temperature organic Rankine cycles (ORC)**

Utilize low energy density sources like

Biomass, low intensity solar, low temperature geothermal

Using organic fluids (eg. pentane) with appropriate thermodynamics

Solar thermal energy conversion image removed due to copyright restrictions.

Please see:


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Please see:

http://www.evworld.com/images/otec_vholstein.jpg