8.21 The Physics of Energy
Fall 2009

8.21 Lecture 12

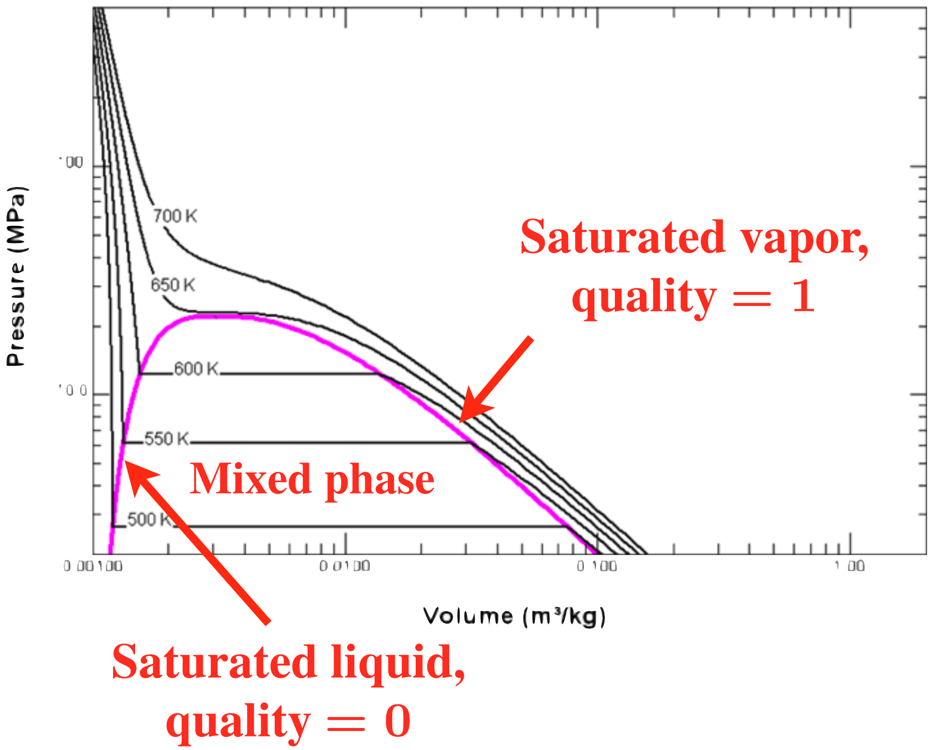
Phase Change Energy Conversion II

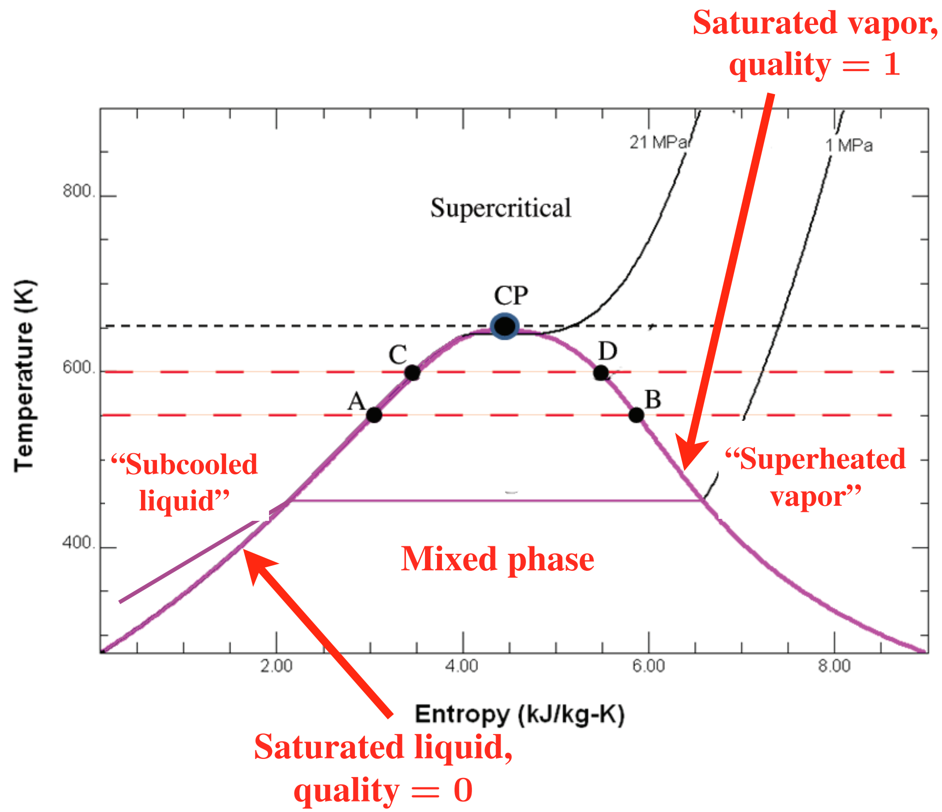
October 5, 2009

- 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

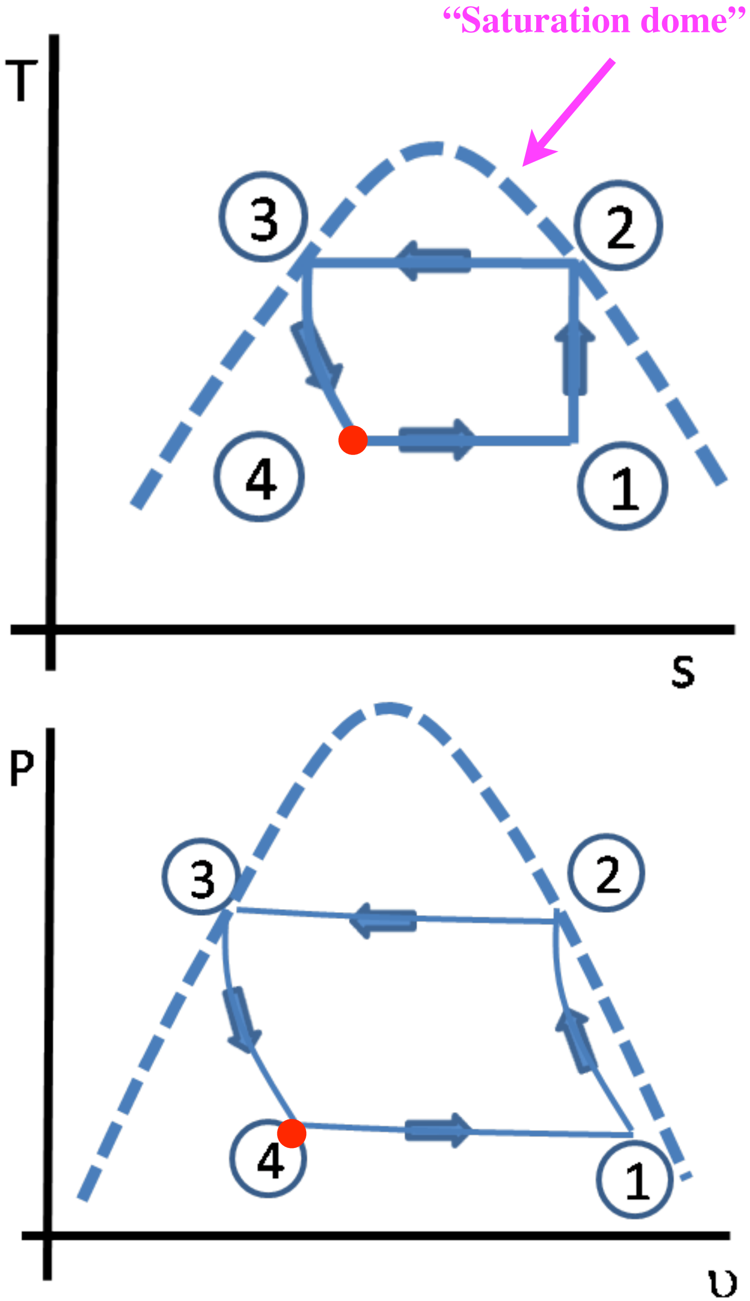
- Marks end of Part I of the course on the "Uses of Energy". Wednesday begins Part II on "Energy Sources"

Reminder: Thermodynamics of phase change:





Let's build a vapor-compression cycle air conditioner



So now lets 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 ⇒ enthalpy of fluid increases:

  Must increase quality (change liquid to vapor)

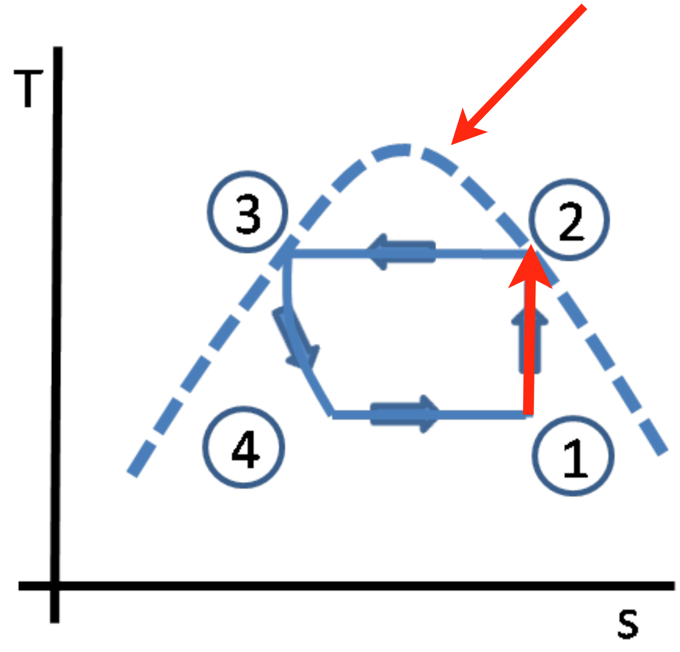
- Result: hot, high pressure, saturated vapor at ②.

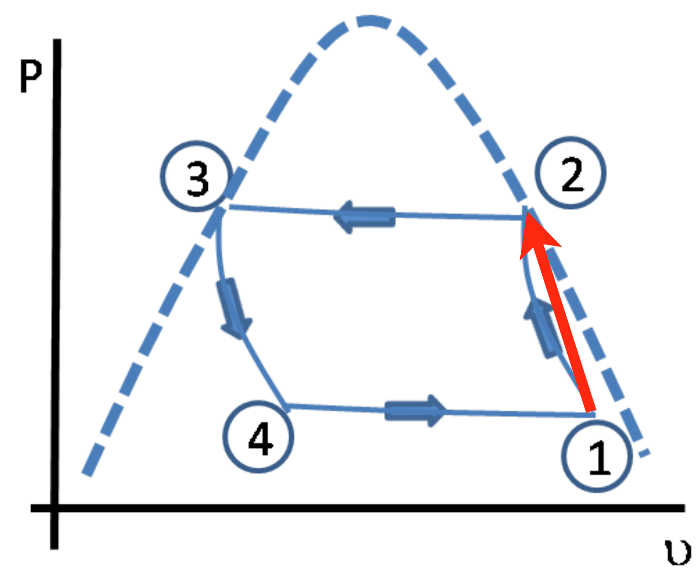
  - ⋆ W_{12} done on fluid
  - ⋆ $Q_{12} = 0$

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

$$\begin{aligned} dH &= dU + pdV + V dp \\ dQ &= dU + pdV = 0 \quad So, \\ dH &= V dp \\ \Delta H &= \int_{p_L}^{p_H} dp\, V > 0 \end{aligned}$$

Saturation Dome





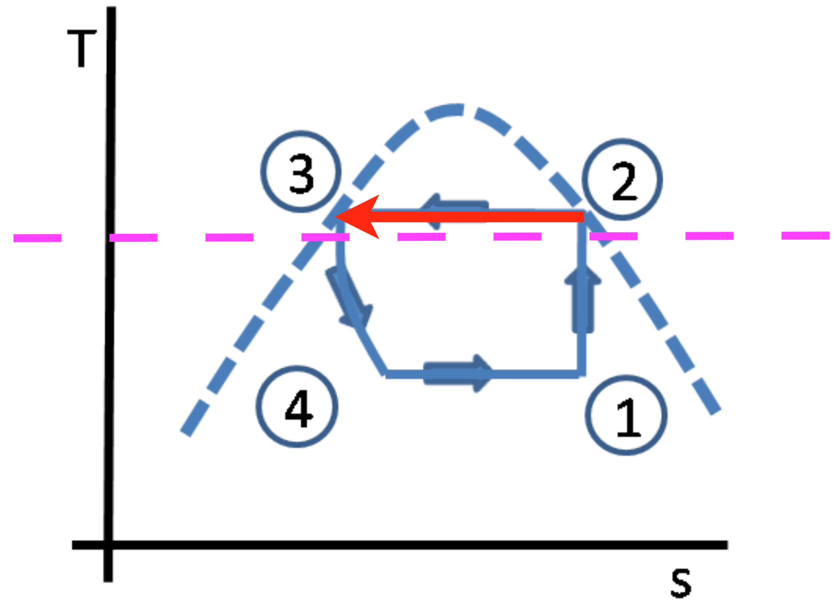
Step [23] isothermal condensation

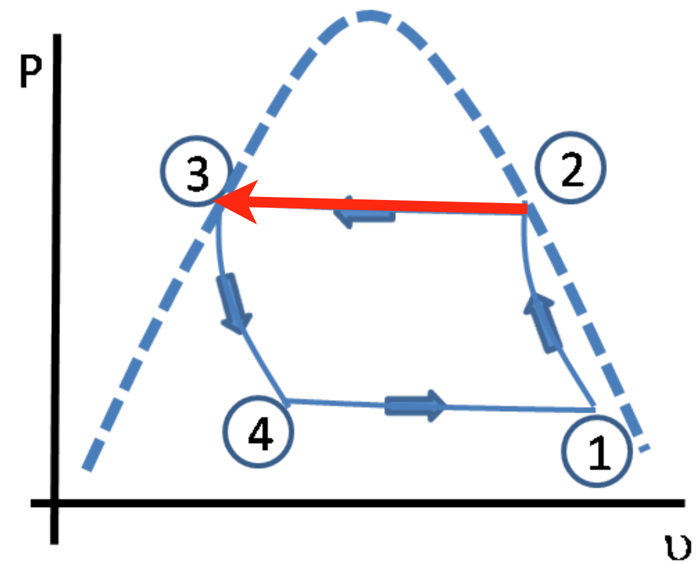
- Start at ②

  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.
  - ⋆ $W_{23} = 0$
  - ⋆ $Q_{23} = Q_H$
- *Condensor* is placed in warm zone (eg. outside refrigerator or home living space)

T_H exceeds temperature of hot environment

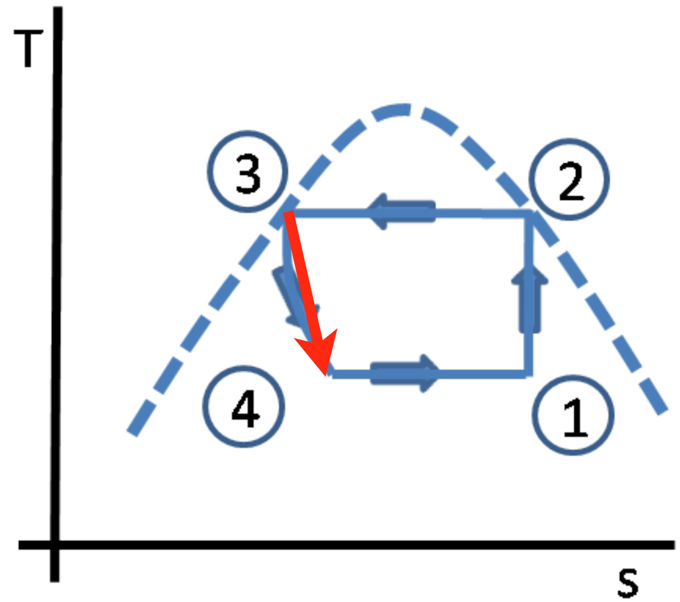


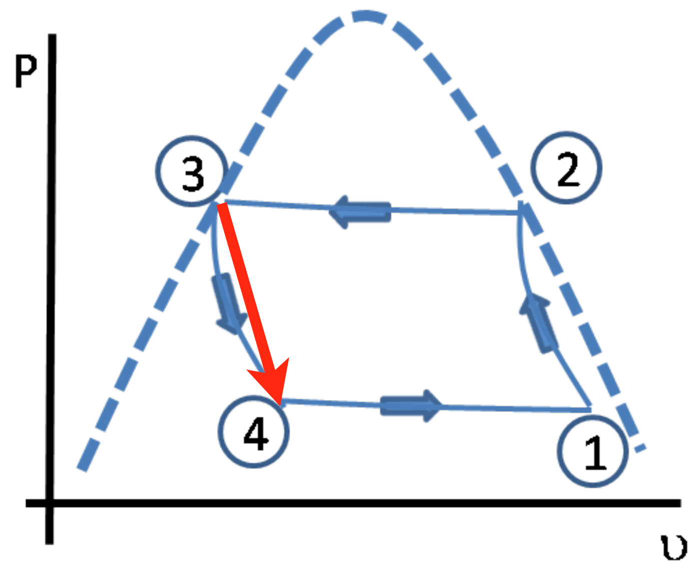


Novel!

Step [34] iso-enthalpic expansion

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





Expansion of saturated liquid through a nozzle

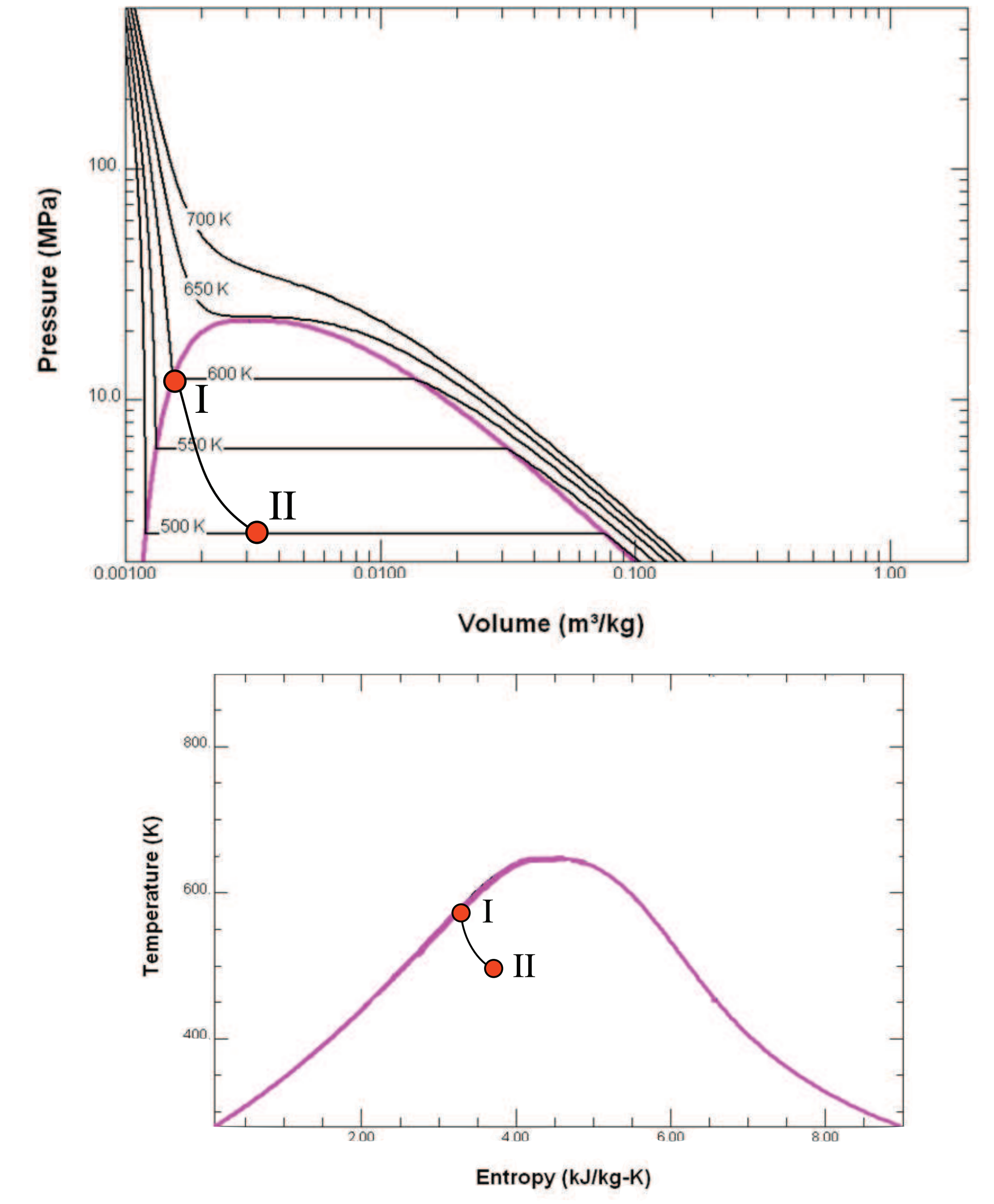
- ⋆ Pressure decreases and volume increases.
- ⋆ Starting point I at saturation

  Moves into mixed phase at II
- ⋆ Trace in ST diagram

  Remember $\Delta S > 0$.

  Temperature must decrease

  Quality (fraction of vapor) must increase



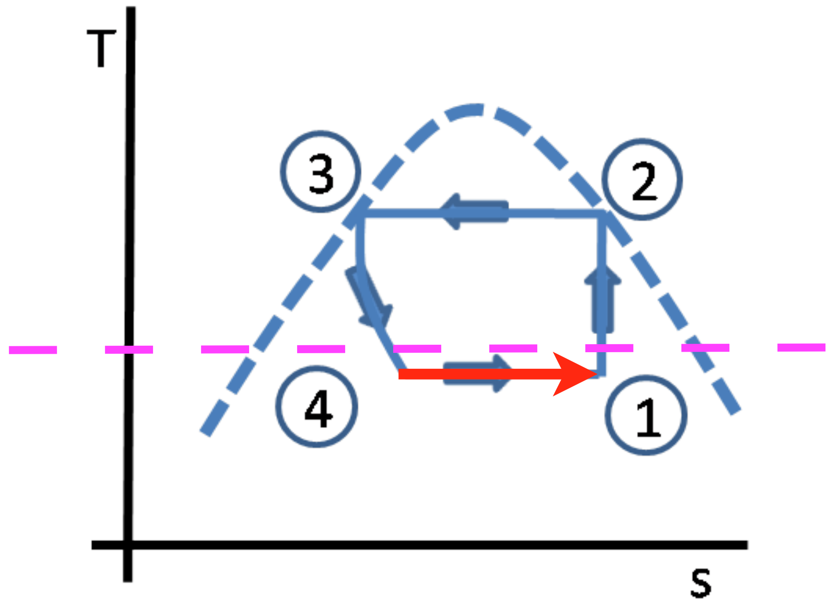
Step [41] isothermal evaporation

- Start at ④

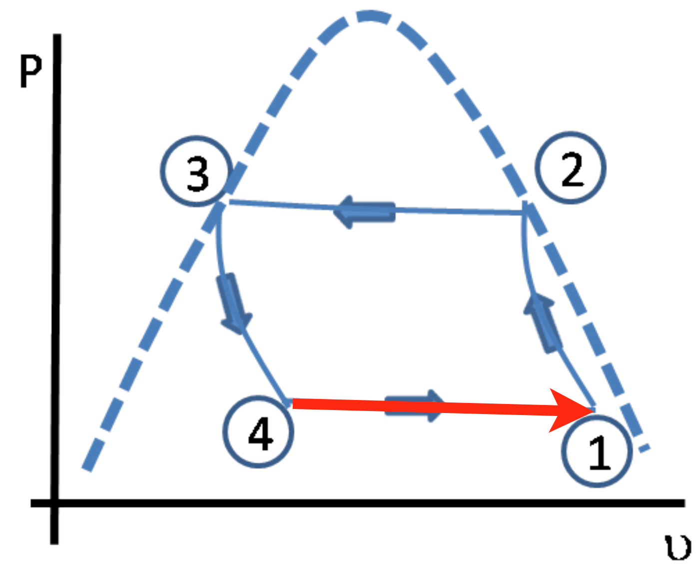
  Liquid rich mixed phase at T_L and P_L

- 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.



T_L is below temperature of hot environment



Summarizing energy flow

⋆ Work done only in compressor: $W_{[12]}$

⋆ Heat removed from low T: $Q_{[41]}$

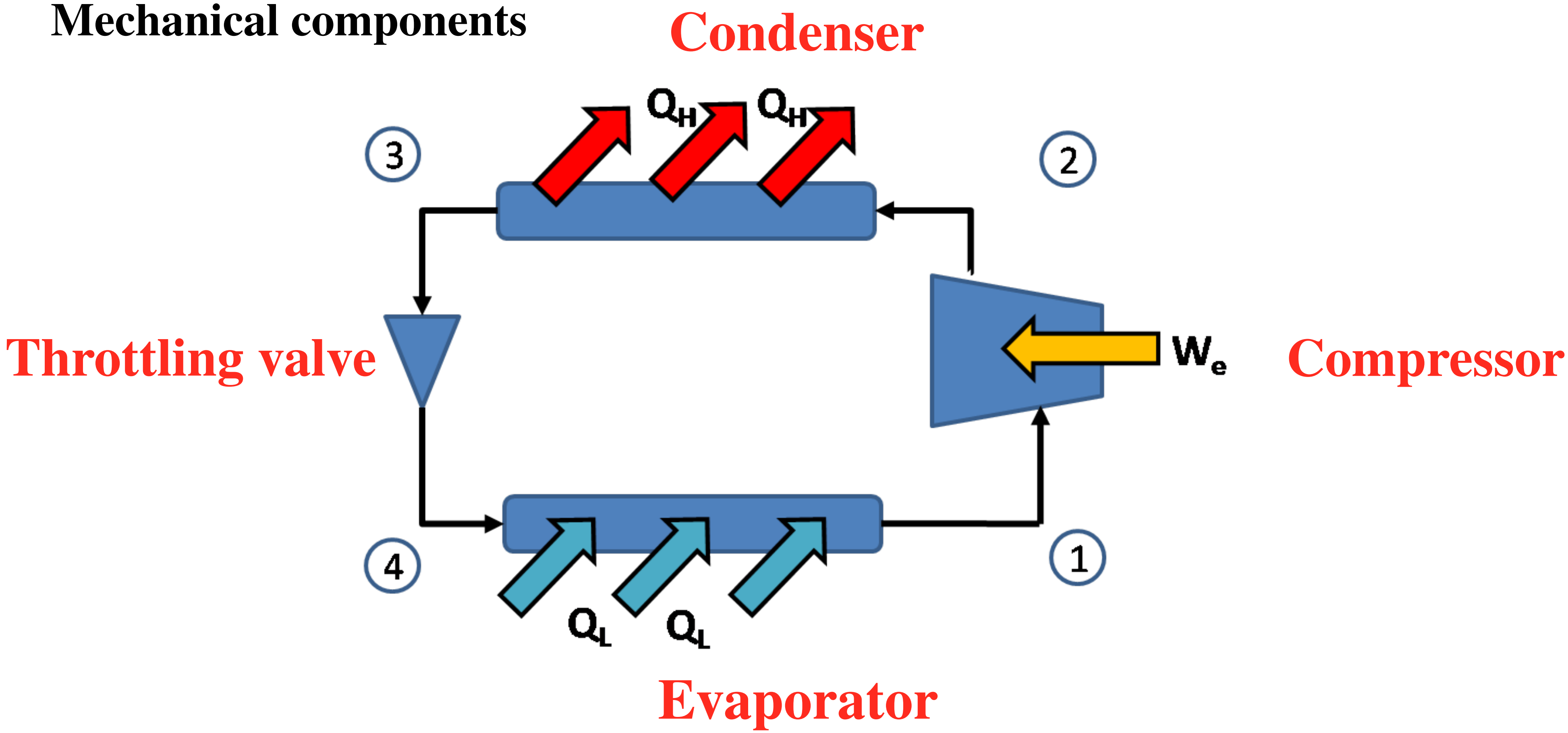
Heat ejected to high T: $Q_{[23]}$

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

Entropy

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

Mechanical components



A scroll compressor

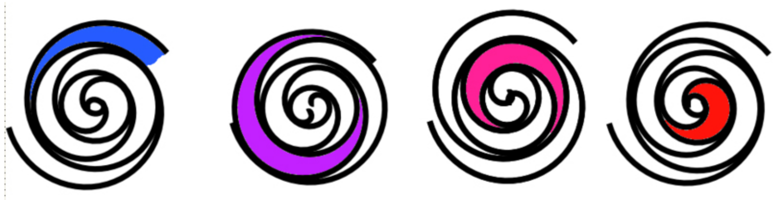


Image from public domain.

A screw-type compressor

From http://commons.wikimedia.org/wiki/File:Lysholm_screw_rotors.jpg

Same principle as throttle

Hair spray image removed due to copyright restrictions.

Please see:

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

Condenser for refrigerator

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Please see:

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

Evaporator for air conditioner

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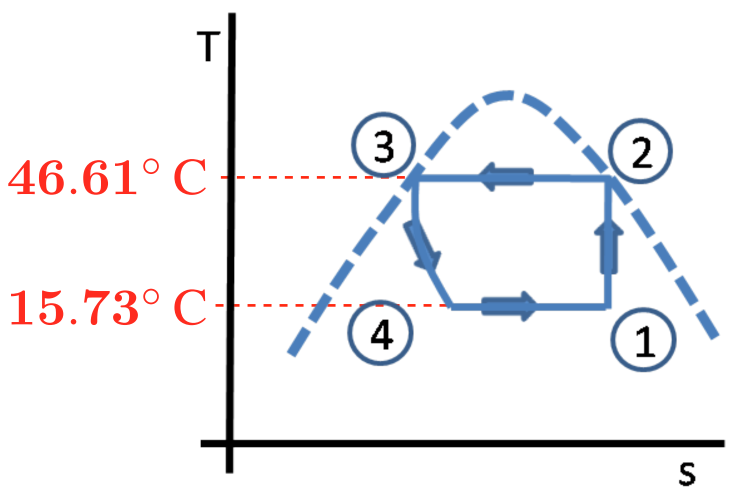
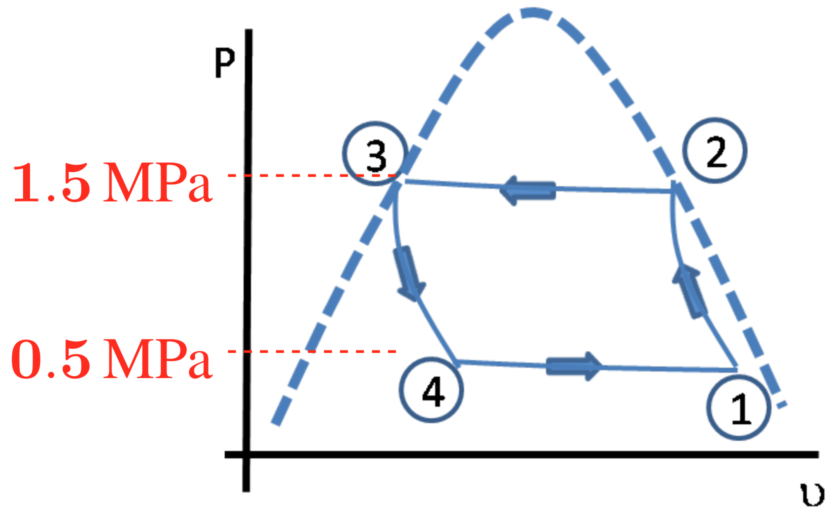
Please see:

http://img.diytrade.com/cdimg/520742/3323685/0/1173261417/A_C_Evaporator.jpg

A quasi-realistic implementation of
The Ideal Vapor Compression Cycle





Stage	T (C)	P (MPa)	energy ($\frac{kJ}{g}$)	enthalpy ($\frac{kJ}{kg}$)	entropy ($\frac{kJ}{kgK}$)	quality
1	15.73	0.5	218.28	238.5	0.83968	0.9830
2	46.61	1.2	236.17	256.23	0.83968	1
3	46.61	1.2	99.065	100.14	0.35107	0
4	15.73	0.5	92.425	100.14	0.3607	0.2390

Performance

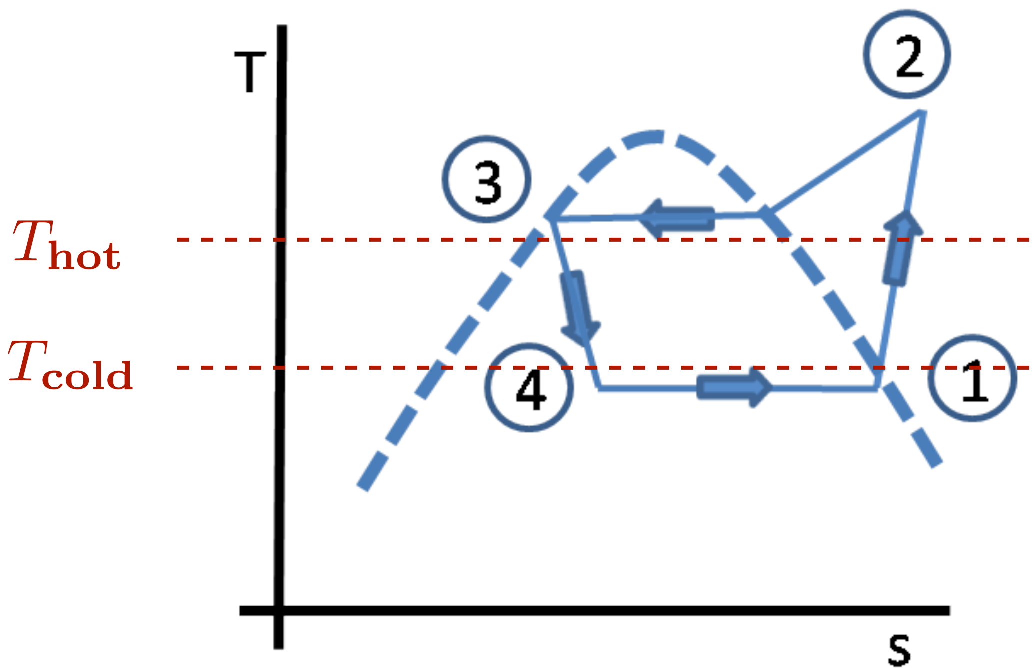
- ⋆ $\Delta W_{[12]} = 17.73$ kJ/kg
- ⋆ $\Delta Q_{[41]} = 138.13$ kJ/kg
- ⋆ CoP = 138.13/17.73 = 7.79
- ⋆ 5 tons cooling (?) = 17.5 kW
- ⋆ $\dot{m} = .126$ kg/sec and $P_{\text{electric}} = 2.25$ kW

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

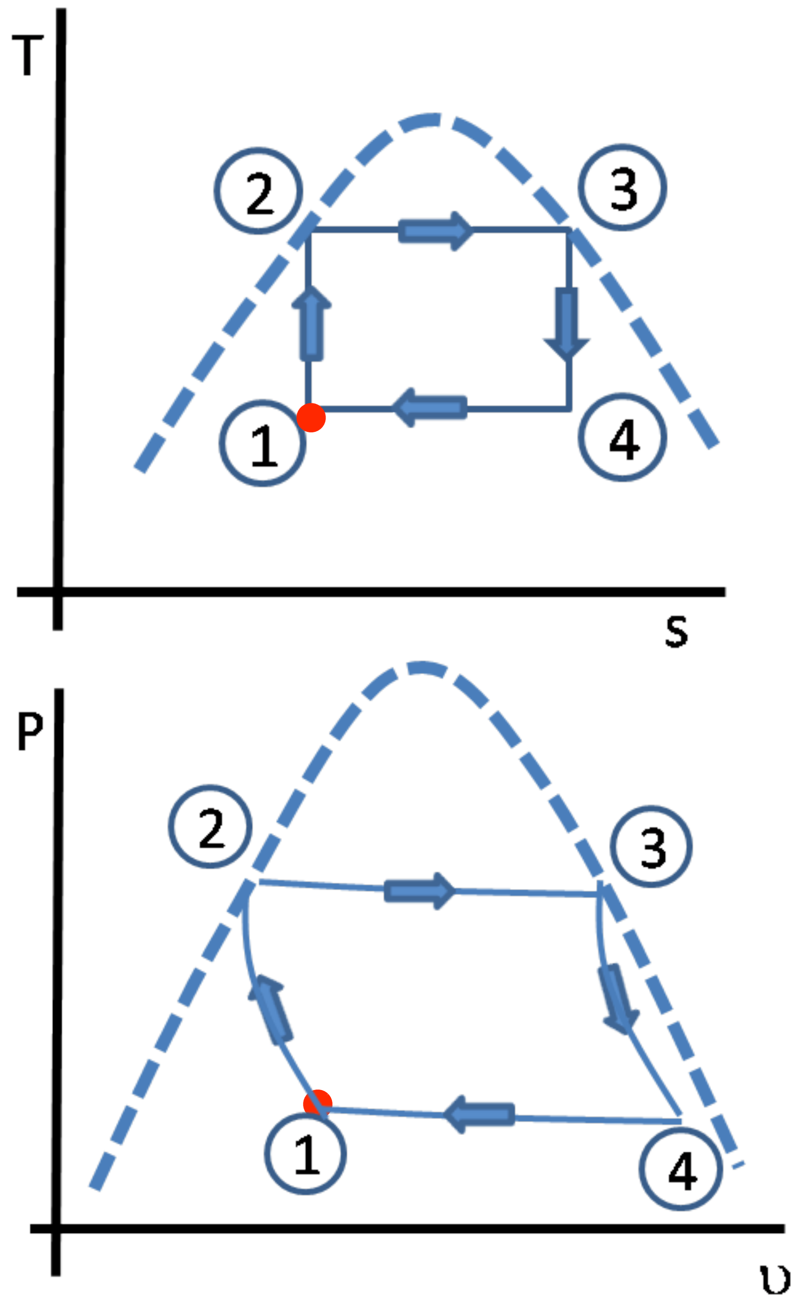
- **Heron of Alexandria circa 1st century AD**
- **Thomas Newcomen (British 17th c), James Watt (British 18th c), developed reciprocating (pistons and cylinders, etc.) steam engines.**
- **Charles Parsons (also British, 19th-20th c), developed steam turbine, using *Rankine Cycle*, which revolutionized power generation.**

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).** PUMP
- **Second step: Pure liquid at (T_H, P_H) absorbs heat and converts to pure vapor at (T_H, P_H) .** BOILER
- **Third step: Pure vapor at (T_H, P_H) expands adiabatically (doing work) to mixed phase of high quality at (T_L, P_L).** TURBINE
- **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).** CONDENSER

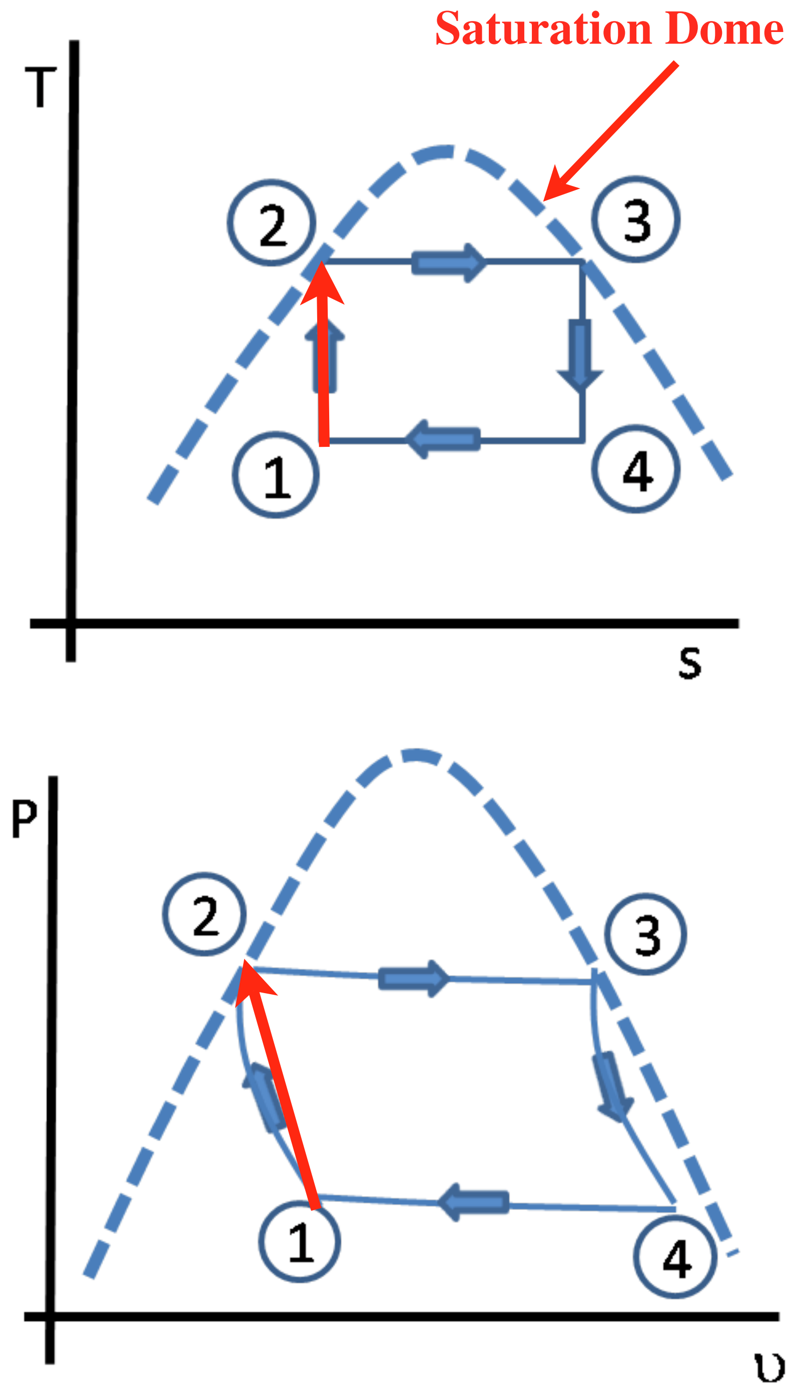


Step [12] iso-entropic (adiabatic) compression

- Enter cycle at ①

  T_L and P_L in mixed phase, mostly water (low quality).

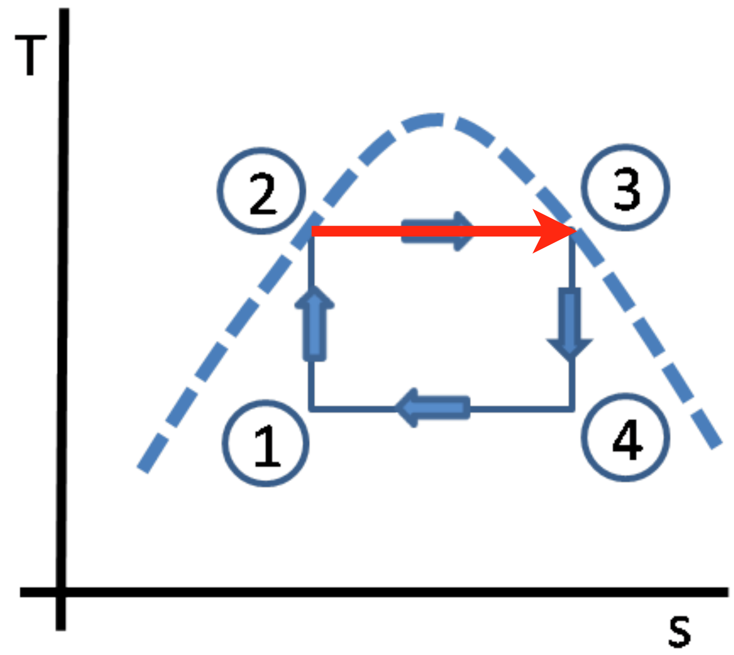
- Compress keeping heat exchange with surroundings to a minimum
- Do work on fluid, but allow no heat transfer ⇒ enthalpy of fluid increases.
- Result: hot, high pressure, saturated liquid at ②.
  - ⋆ $W_{12} = W_{\text{pump}}$ done on fluid
  - ⋆ $Q_{12} = 0$
- Pump

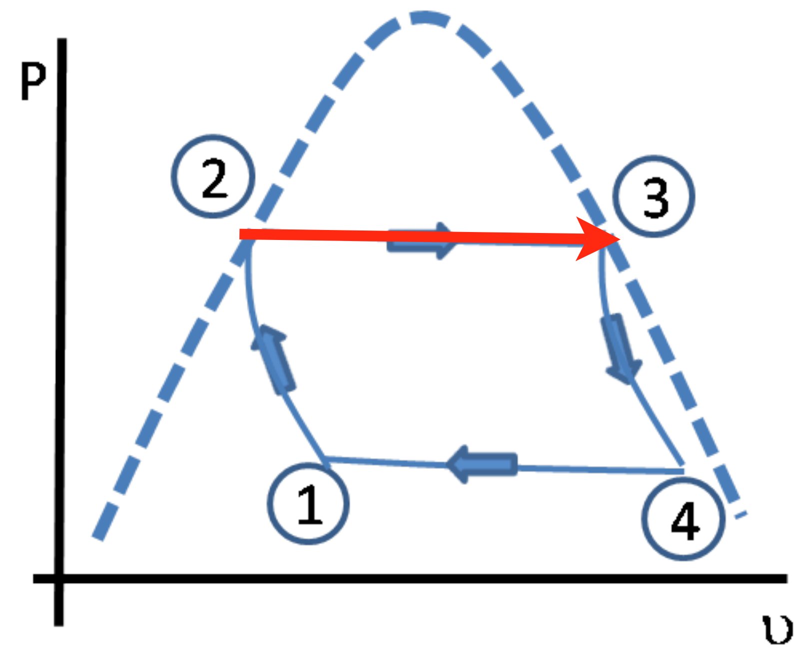


Step [23] isothermal vaporization (boiling)

- Start at ②

  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 ③.
  - ⋆ $W_{23} = 0$
  - ⋆ $Q_{23} = Q_H$

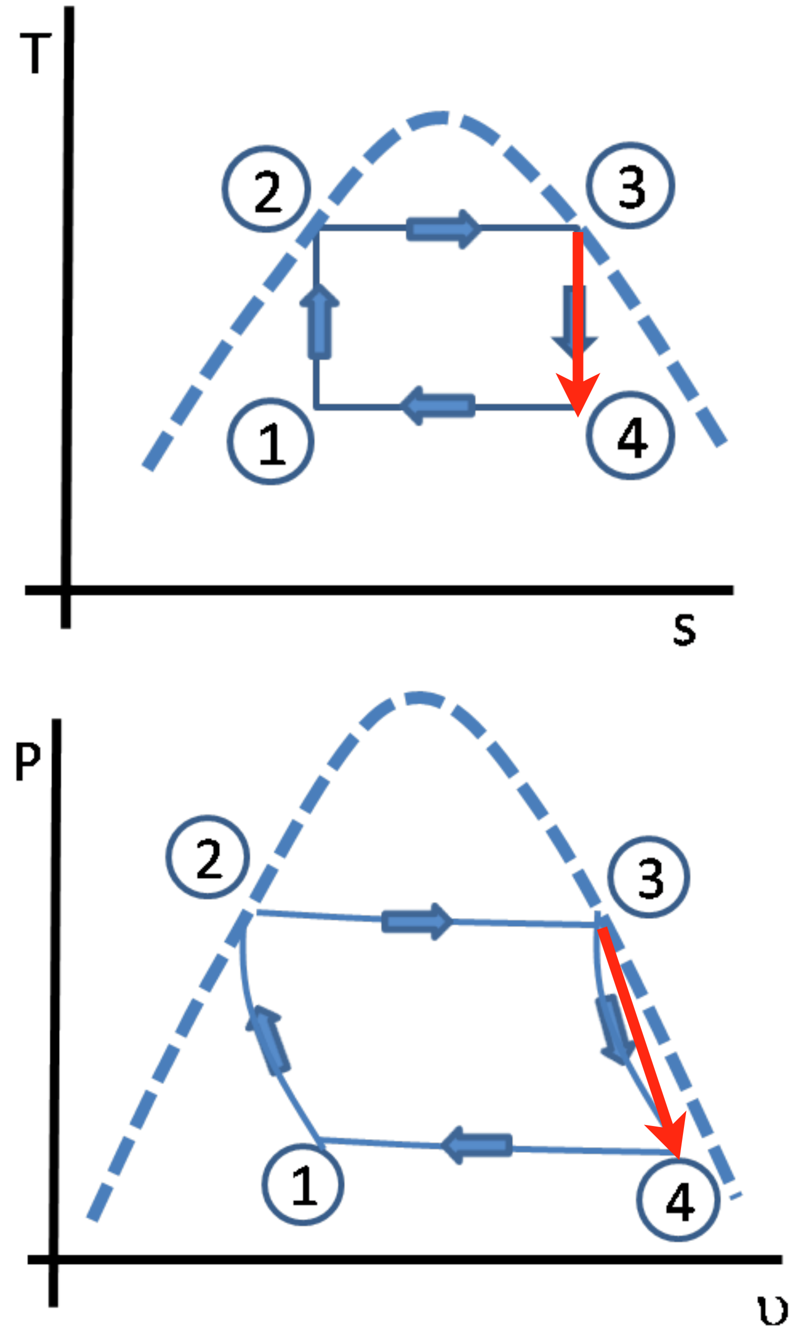




Novel!

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

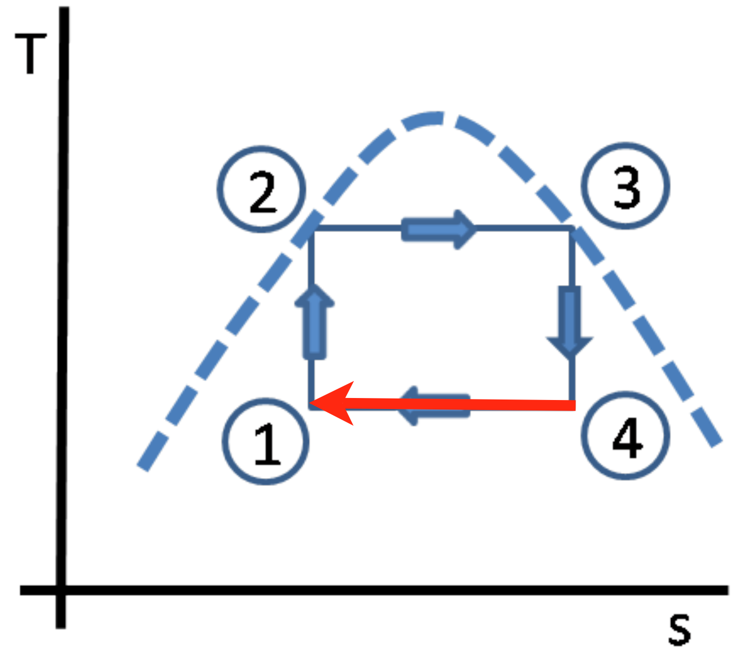
  Vapor rich mixed phase at T_L and P_L

- 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

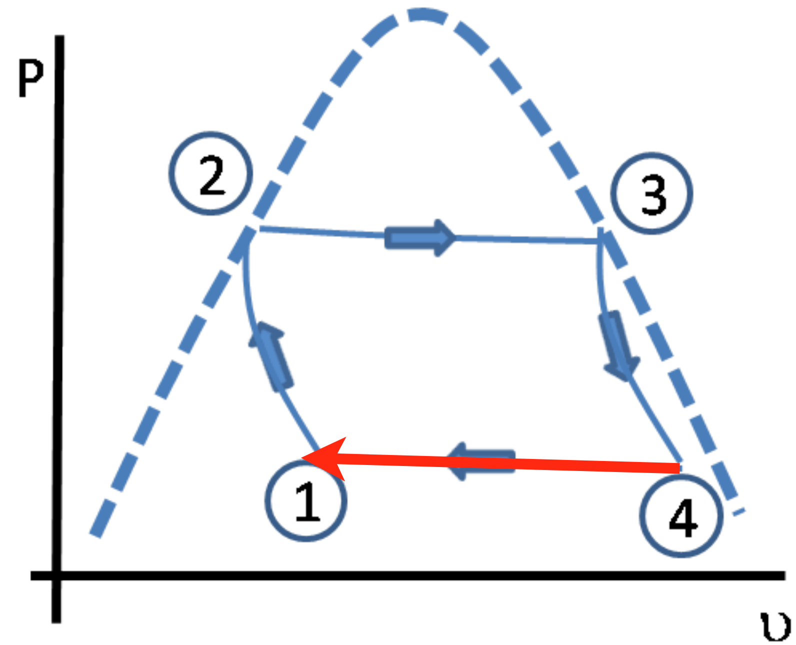
⋆ Net work: $W_{[34]} - W_{[12]}$

Turbine – pump

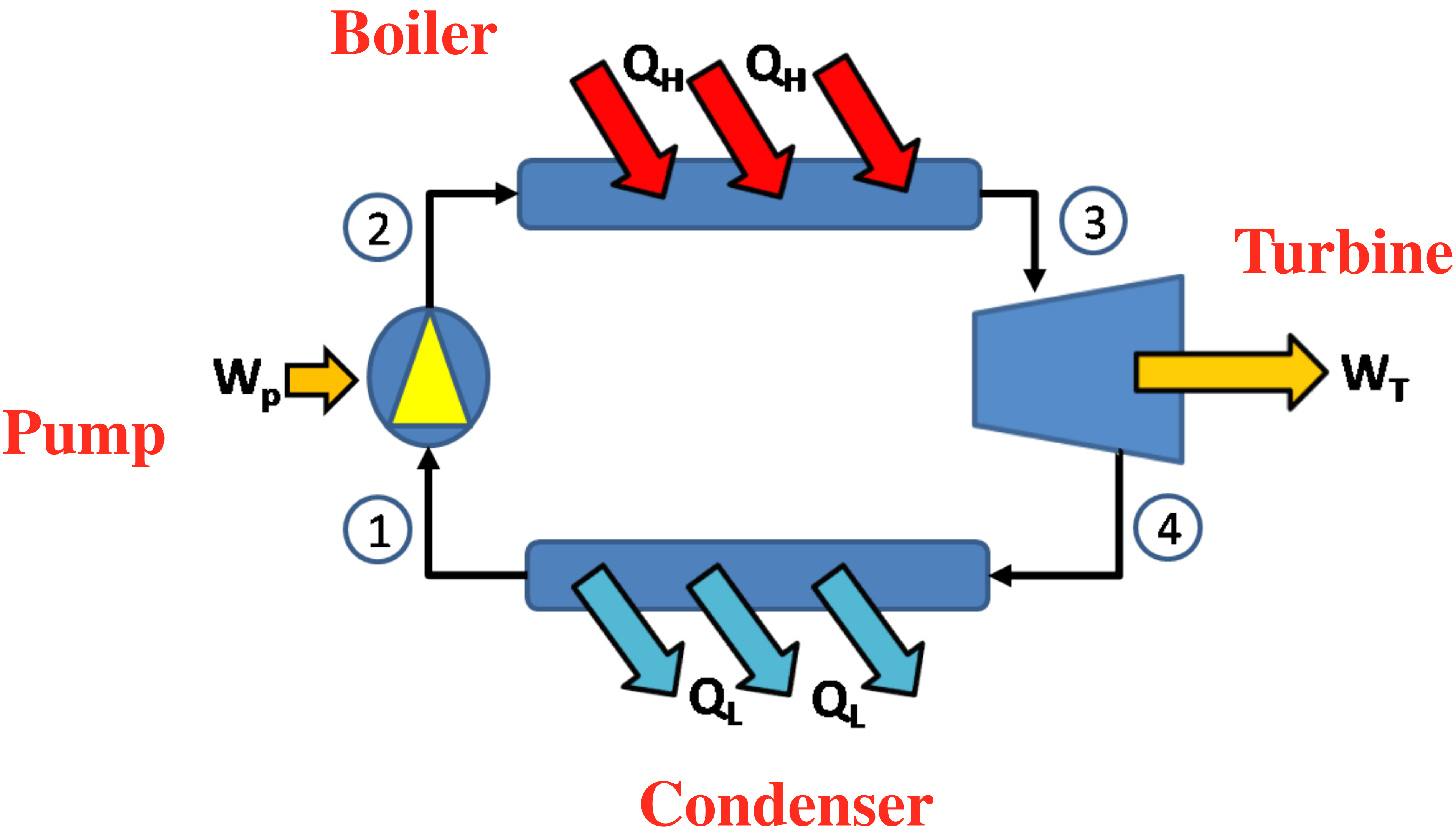
⋆ Heat take from high T: $Q_{[23]}$

Heat ejected to low T: $Q_{[41]}$

$$\text{CoP} = \frac{W_{[34]} - W_{[12]}}{Q_{[23]}}$$



Mechanical components in Rankine Steam Cycle



Please see:
http://nlcs.k12.in.us/oljrhi/brown/power/images/steamturbine.jpg

Important design considerations and a more realistic Rankine Cycle

⋆ I Pumps

Real pumps are single phase devices, for pressurizing liquids.

Much easier to pressurize a liquid than a gas

So ① must be moved to saturation

Forces massive condensation systems

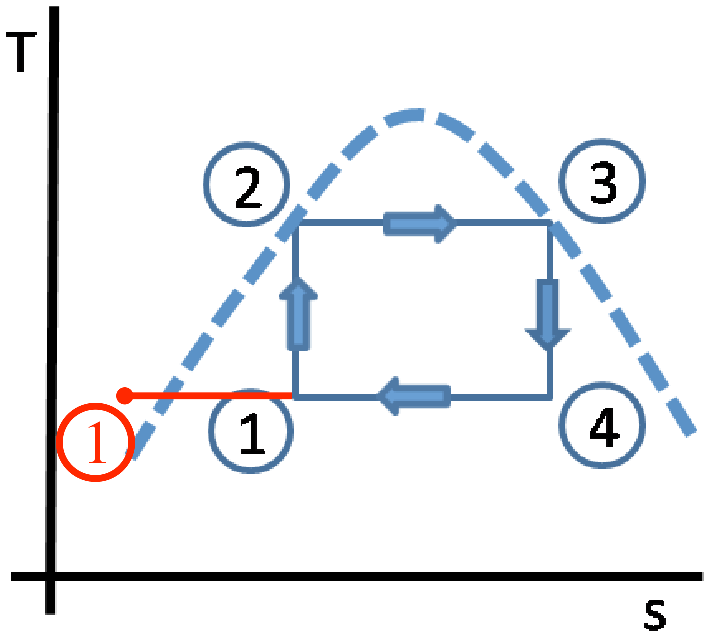


Image from http://commons.wikimedia.org/wiki/File:Drax_cooling_tower.jpg

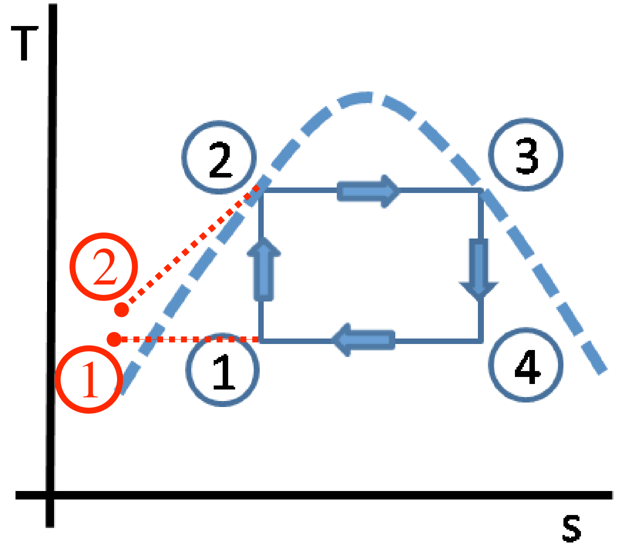
Important design considerations and a more realistic Rankine Cycle

⋆ 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



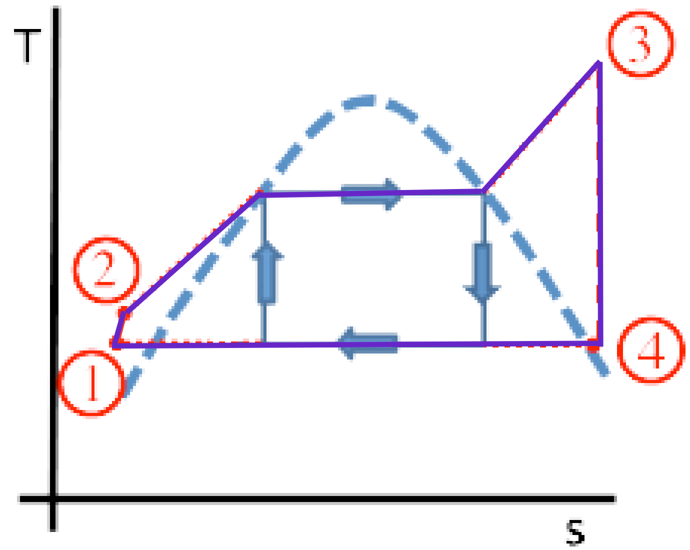
⋆ III Turbines

High performance turbines cannot tolerate a mixed phase

Droplets of liquid damage rotors and quickly degrade performance

Vapor input to turbine must be superheated

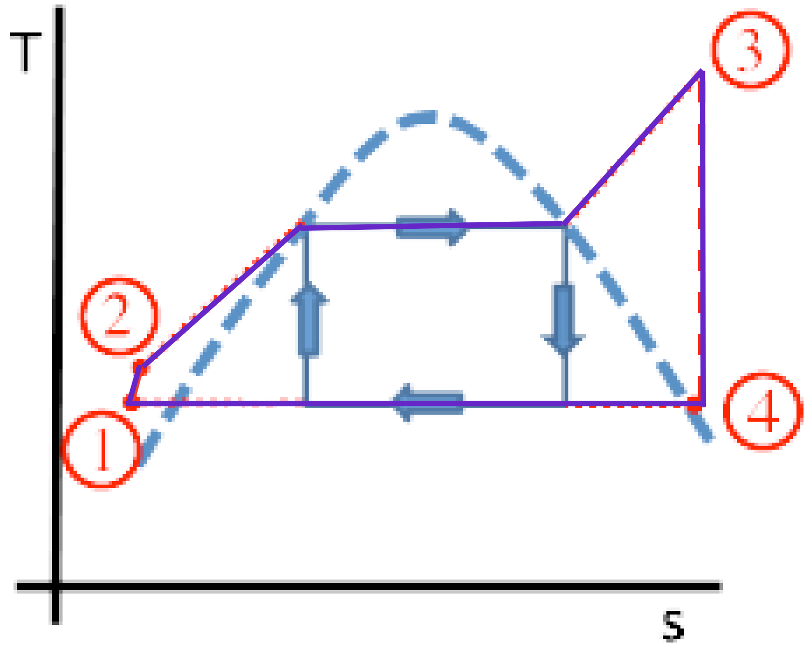
And fluid at outlet must be $\gtrsim 99\%$ vapor



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!

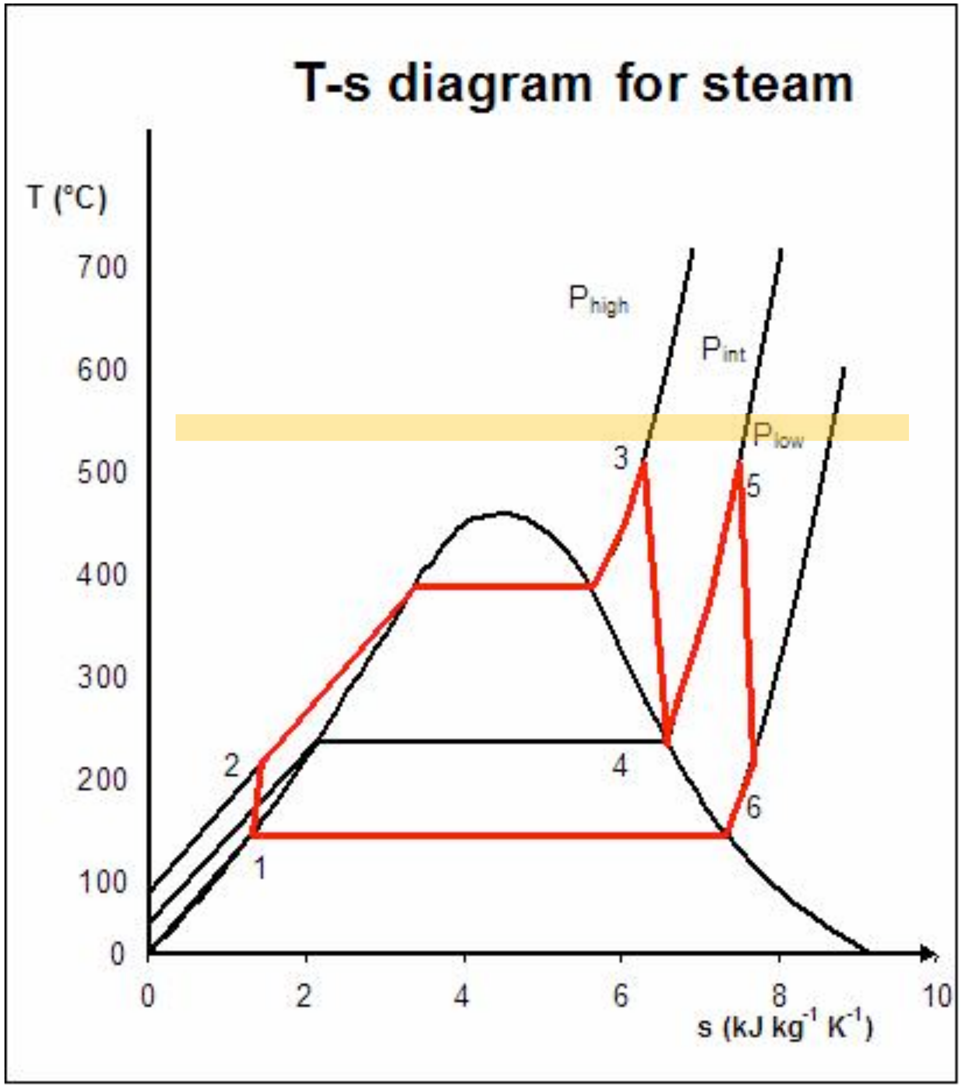
    That is: Use the steam for space heating!



Rankine Cycle with Reheating

Improving the Rankine Cycle

- ⋆ Use higher temperature and pressure
- ⋆ Must keep turbine out of mixed phase
- ⋆ Must not let T_H exceed $\sim 550 - 600°\text{C}$
- ⋆ Solution: Two turbines with reheating!



Rankine Cycle with Regeneration

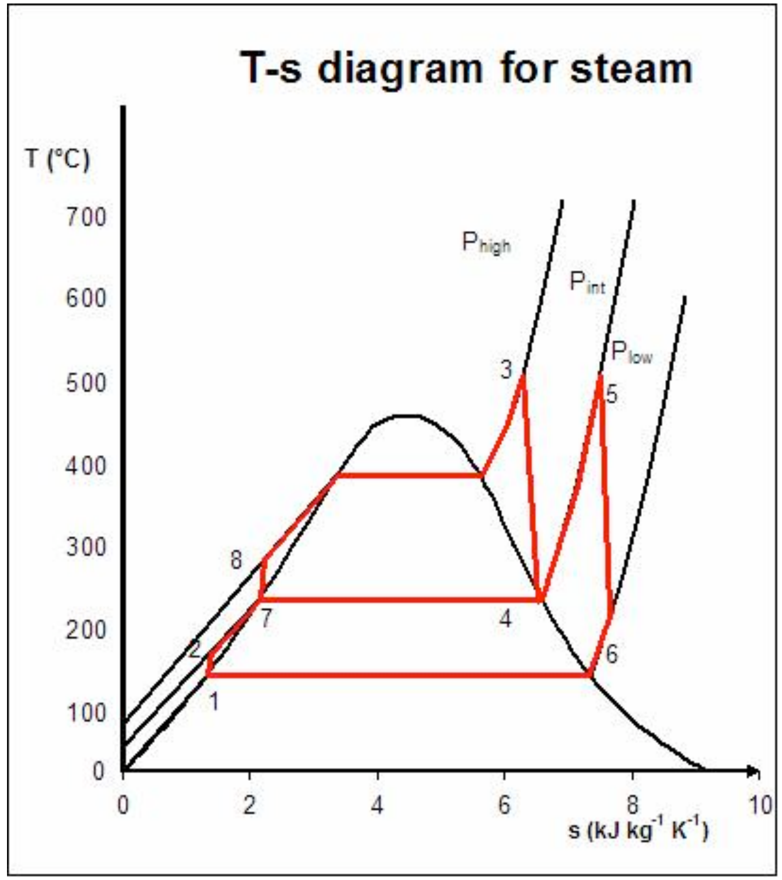
Rankine with regeneration:

- **Commonly used in actual power plants**
- **Two turbines in series**

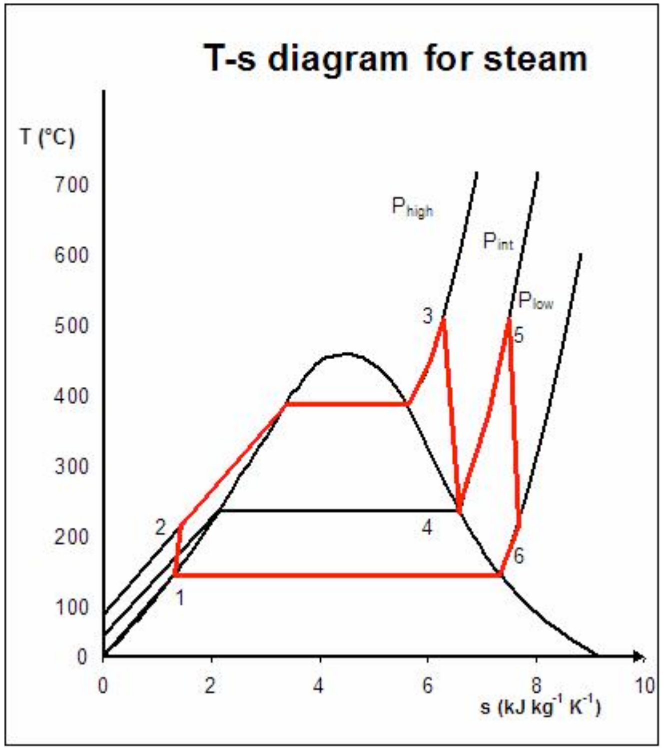
  Condensed subcooled liquid at ②

  Mixed with steam tapped at ④

  To preheat to saturated liquid at ⑦



More complex Rankine cycles



Rankine with reheating:

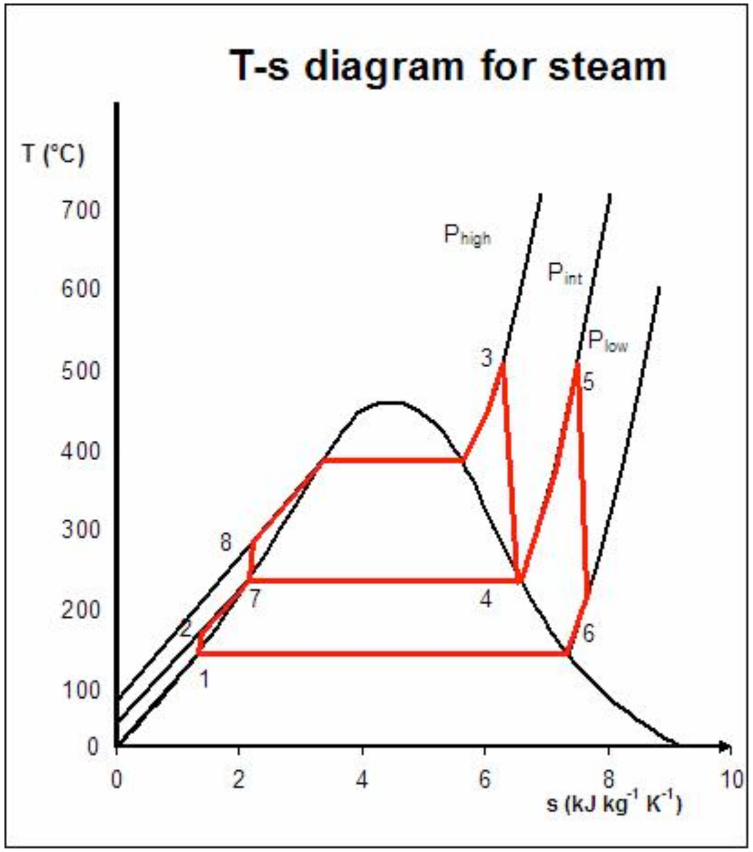
- **Two turbines in series**

  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

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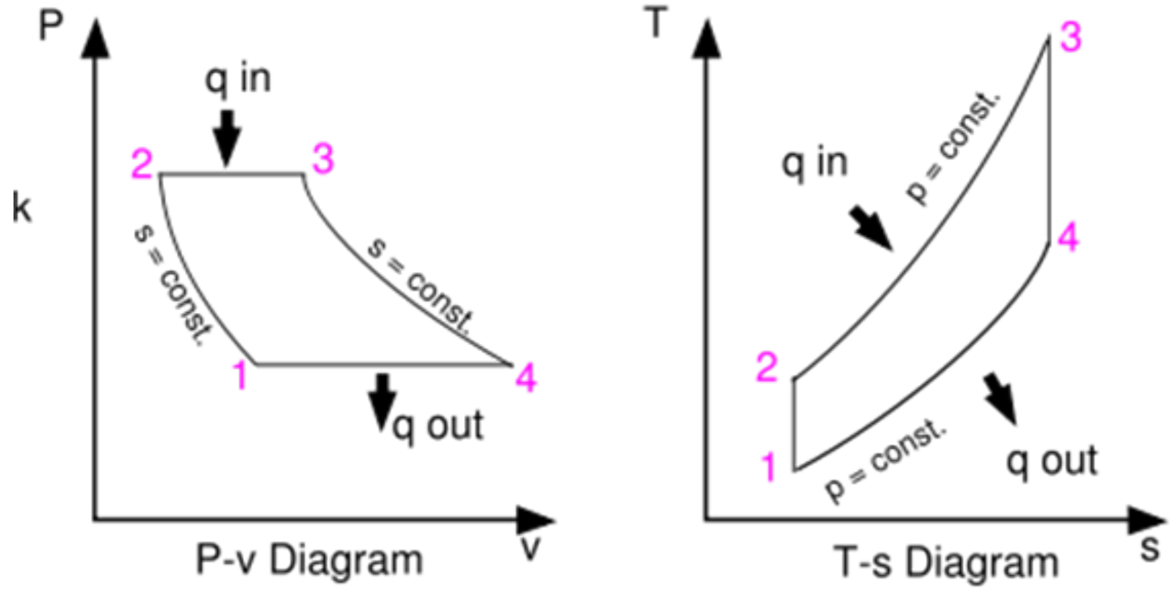
  To preheat to saturated liquid at ⑦

Brayton-Rankine combined cycles

Brayton Gas Turbine Cycles

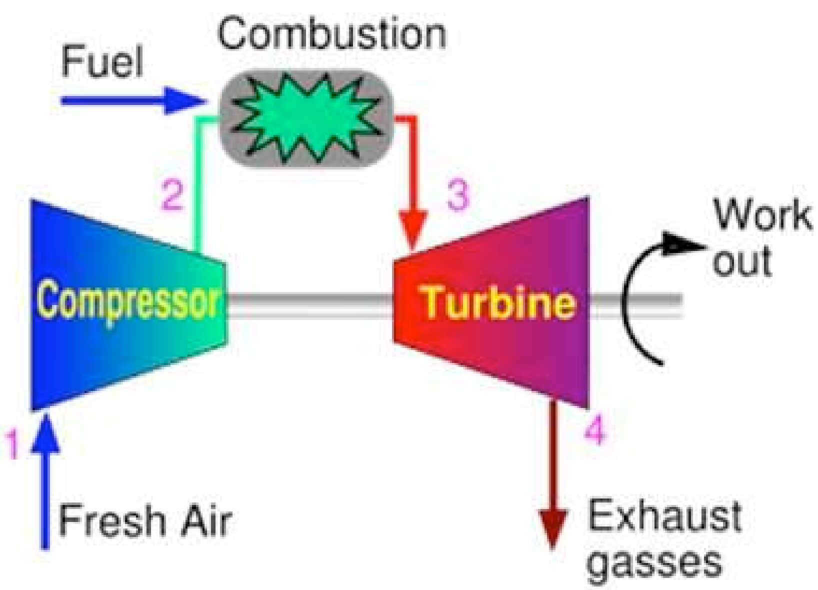


Open cycle gas fired turbine

- ⋆ What's the idea? Burn natural gas to produce high T and high P vapor

  Directly powers turbine

- ⋆ Very high temperatures $\sim 1200°$C and efficiencies $\sim 35-42\%$.

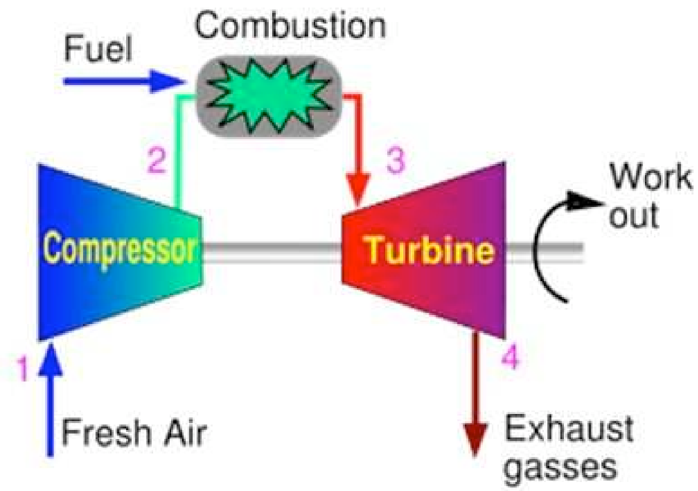


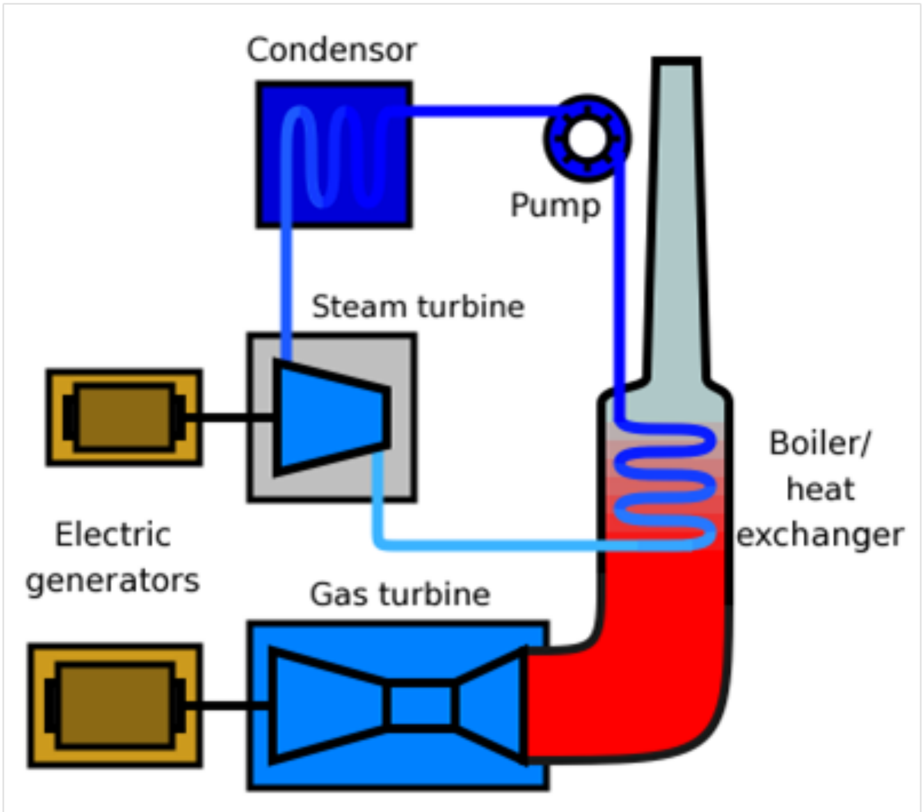
- ⋆ Elements in cycle
  - [12] Fresh air enters compressor: Adiabatic compression
  - [23] Combustion: Isobaric heating
  - [34] Turbine: Adiabatic expansion
  - [41] Exhaust: Isobaric cooling

Brayton Gas Turbine Cycles

Combine Brayton Gas Cycle with Rankine Steam Cycle

- ⋆ Very high temperatures $\sim 1200°$C and efficiencies $\sim 35 - 42\%$.
- ⋆ By-product gases from gas turbine are hot enough, $\sim 500°$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)

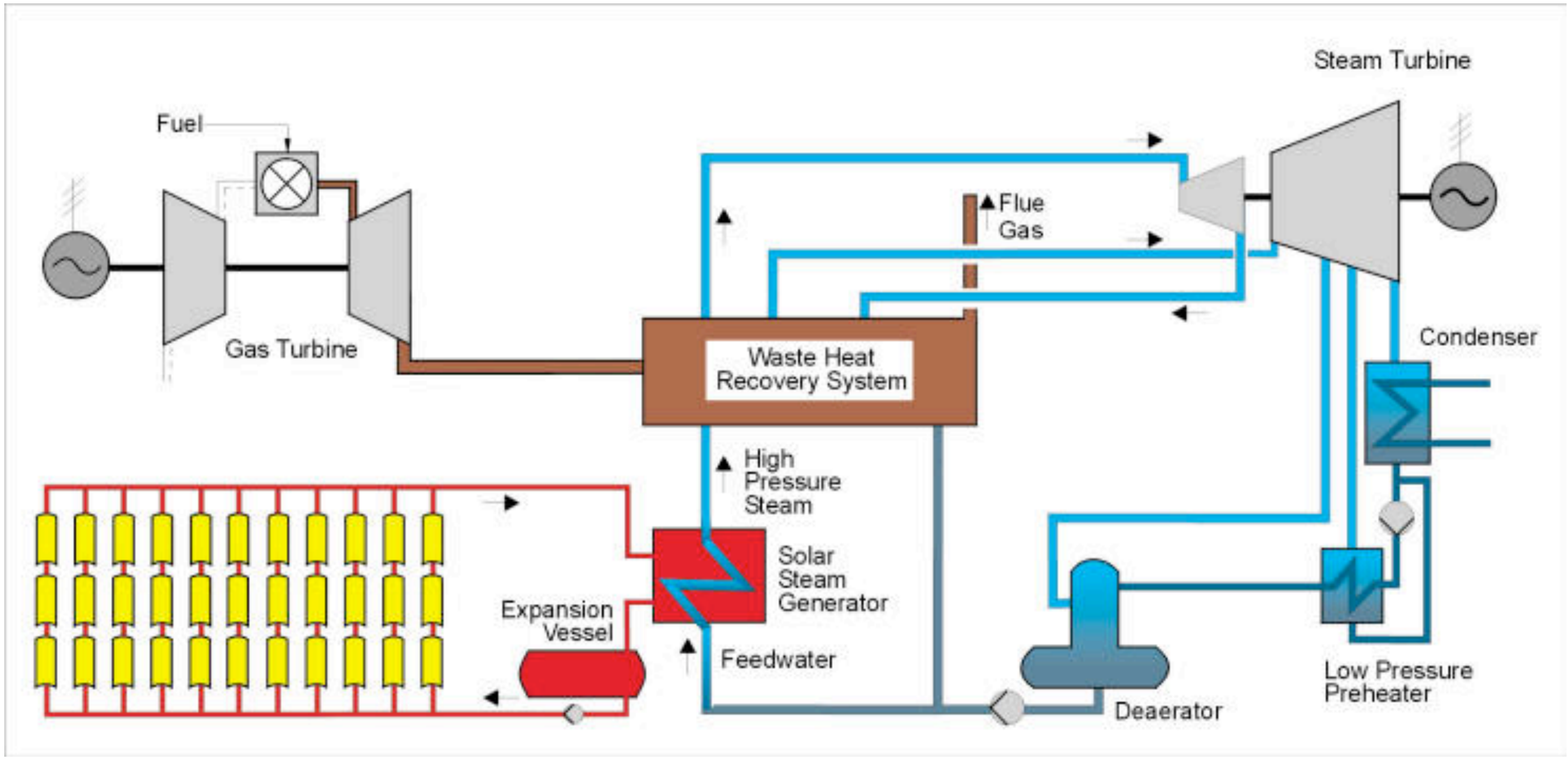




Gas Turbine Combined Cycles

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

Please see:

http://www.inhabitat.com/wp-content/uploads/solarsalt1.jpg

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