Chemical Engineering 612

Reactor Design and Analysis

Lecture 19

Balance of Plant

Thermodynamics I

Spiritual Thought

Matthew 22: 37-39

37 Jesus said unto him, Thou shalt love the Lord thy God with all thy heart, and with all thy soul, and with all thy mind.

38 This is the first and great commandment.

39 And the second is like unto it, Thou shalt love thy neighbor as thyself..

Balance of Plant

- Non-nuclear systems?
- Nuclear Island
- Power Conversion System
- Reactor Control Systems
- Chemistry Systems
- Safety Systems
- Support systems

How to design

- Preliminary Design – conceptual
  - Integral analyses
  - Order of magnitude scopes
- Detailed Design – VERY complete
  - Differential Analyses (simulations)
  - Specific (and accurate) details
- Licensed Design – PRA/Uncertainty
  - Detailed design+
  - Evolves with RAI's
  - Final DCD (9000+ pages)

Integral Design Process

$$\frac{dB_{sys}}{dt} = \frac{d}{dt}\int_{CV} \rho b \, dV + \int_{CS} \rho b \vec{v} \cdot \vec{n} \, dA$$

– Recall that any property can be B_{sys}

- Mass – Continuity Equation

- $0 = \frac{d}{dt}\int_{CV} \rho \, dV + \int_{CS} \rho \vec{v} \cdot \vec{n} \, dA$

- Momentum – Force Vector Balance

- $\sum \vec{F} = \frac{d}{dt}\int_{CV} \rho \vec{v} dV + \int_{CS} \rho \vec{v}\vec{v} \cdot \vec{n} \, dA$

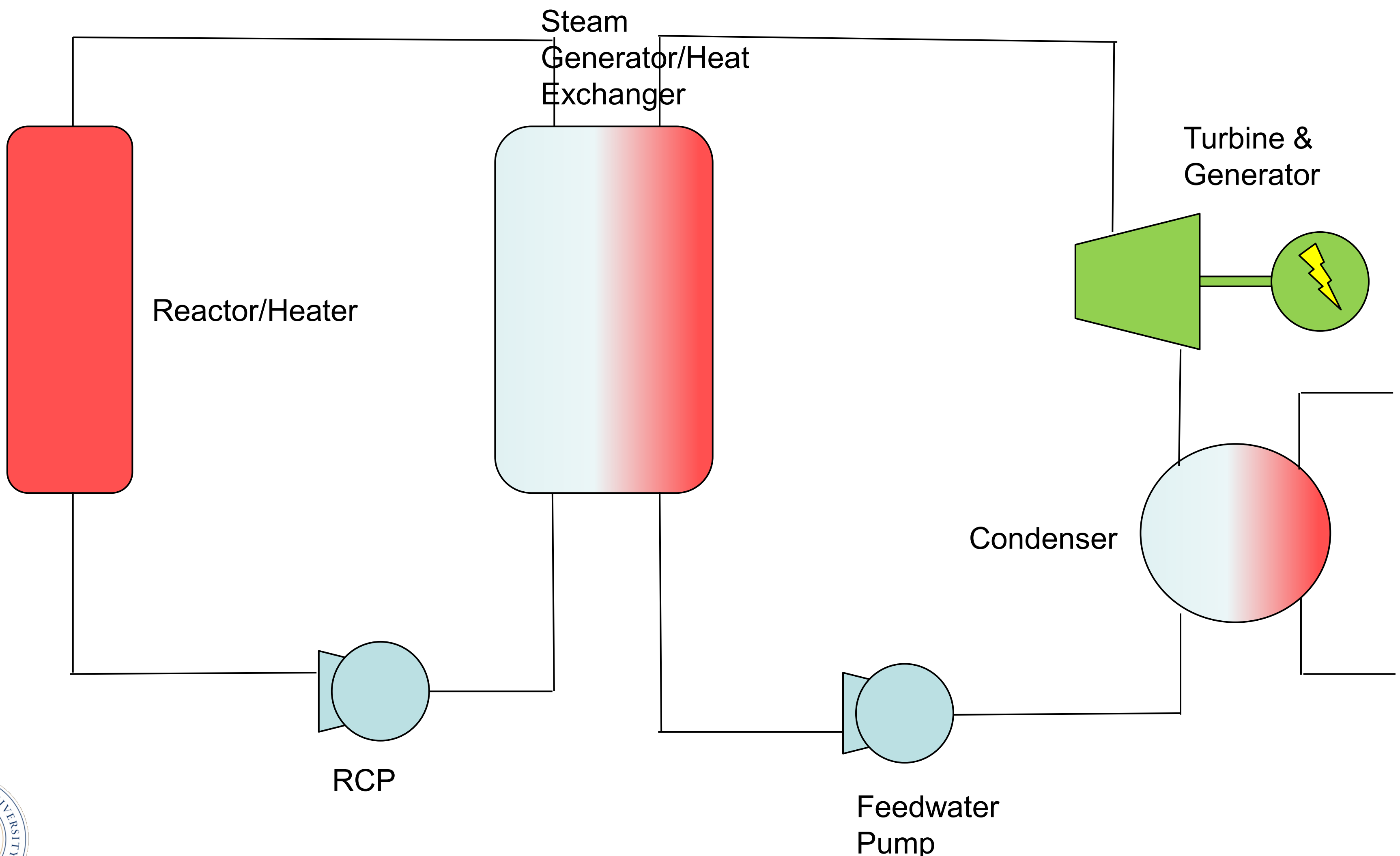
- Energy – Mechanical Energy Balance

$$\frac{dQ}{dt} + \frac{dW}{dt} = \frac{d}{dt}\int_{CV} \rho(u + \frac{1}{2}v^2 + gz)dV + \int_{CS} \rho(u + \frac{1}{2}v^2 + gz)\vec{v} \cdot \vec{n} dA$$

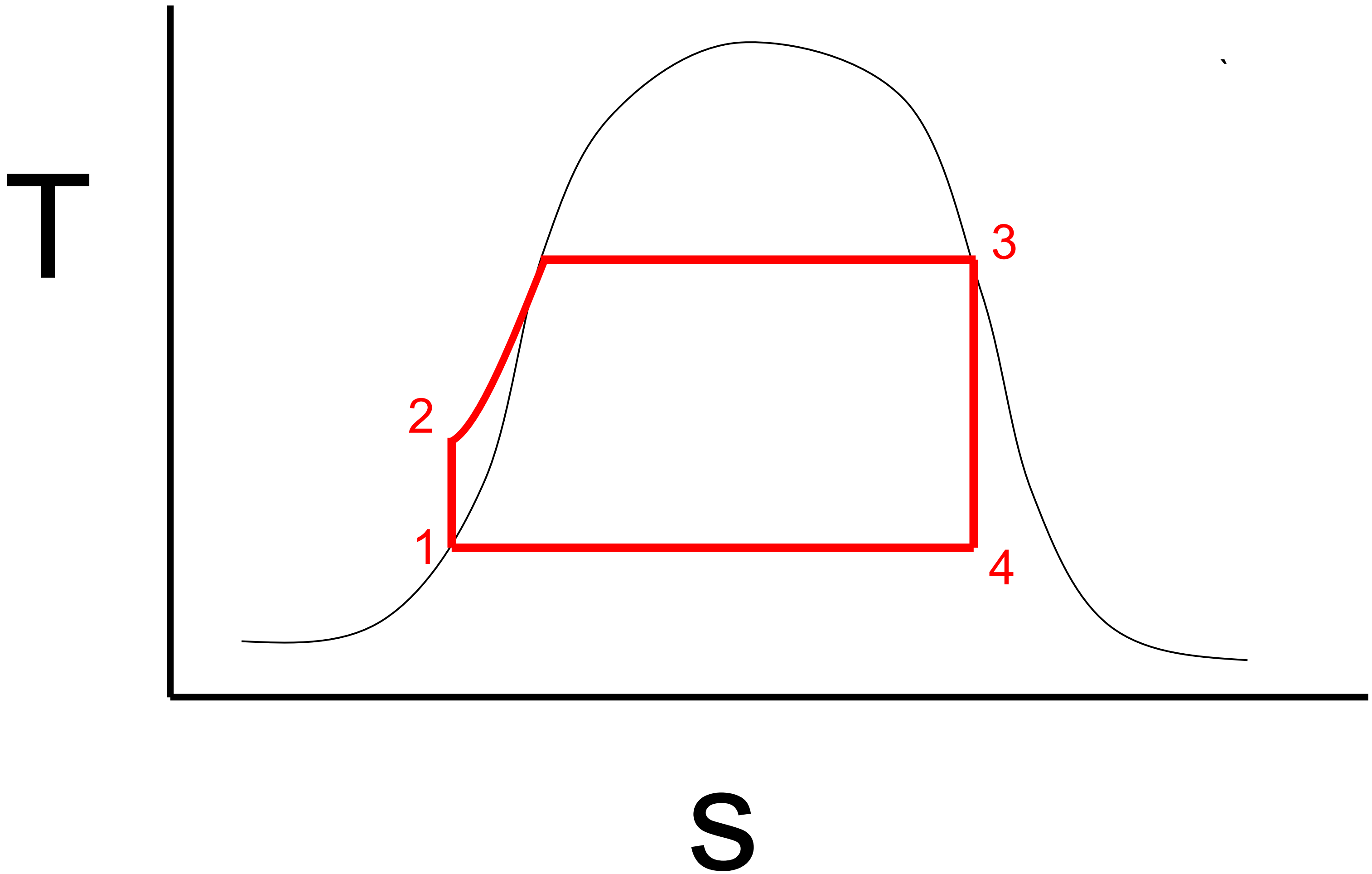
Power Conversion Systems

- Based on 1st and 2nd Thermodynamic laws
  - Eulerian analysis sufficient for design
  - For licensing, eventually need more detail (CFD)
- Several Considerations
  - Maximize T_h and minimize T_c, →max efficiency
  - Radiation Contamination
  - Coolant Interactions (advanced reactors)
  - Type of cycle
    - Brayton vs. Rankine vs. organic Rankine, etc.
  - Enhancements
    - Reheat, regeneration, moisture separation, etc.

Typical Basic PCS Arrangement



T-S Diagram



Thermodynamic Analysis

- Mass Balance
  - $\frac{dB_{sys}}{dt} = \frac{d}{dt}\int_{CV} \rho b \, dV + \int_{CS} \rho b \vec{v} \cdot \vec{n} \, dA$
  - $0 = \frac{d}{dt}\int_{CV} \rho \, dV + \int_{CS} \rho \vec{v} \cdot \vec{n} \, dA$
  - $\frac{dM_{cv}}{dt} = \sum_i m_i$
- Energy Balance
  - $\frac{dE_{cv}}{dt} = \sum_i m_i \left(h_i + \frac{{v_i}^2}{2} + gz_o\right) + \dot{Q} + \dot{W}$
- Entropy Balance
  - $\frac{ds_{cv}}{dt} = \sum_i m_i \, \hat{s}_i$

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Reactor Analysis

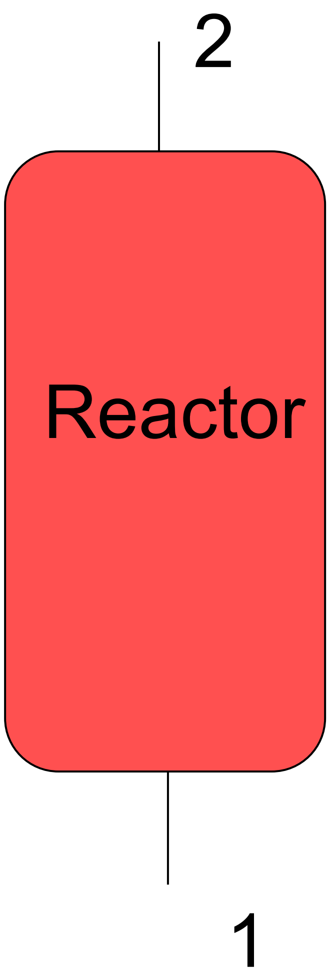
- Steady State
  - Mass Balance

$$\dot{m}_1 = \dot{m}_2$$

  - Energy Balance
  - $\frac{dE_{cv}}{dt} = \sum_i m_i \left(h_i + \frac{{v_i}^2}{2} + gz_o\right) + \dot{Q} + \dot{W}$

$$\dot{Q} = \dot{m}C_p\Delta T = \dot{m}(\Delta h)$$

  - $\widehat{\mathrm{Q}} = C_p\Delta T$



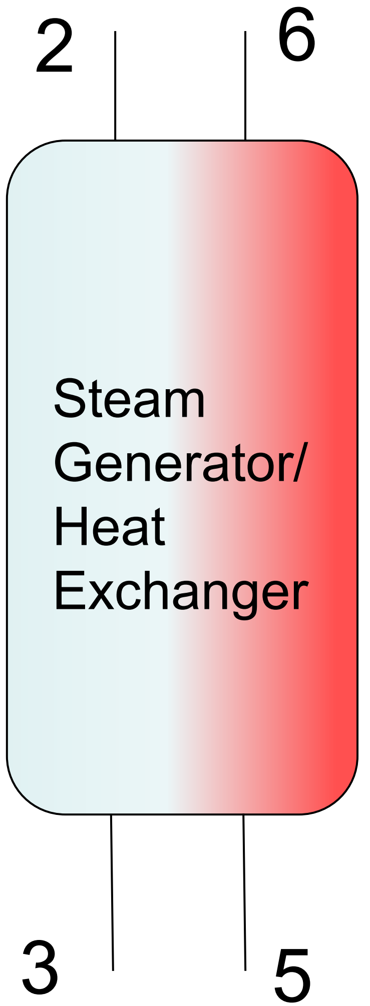
Steam Generator

- Steady State
  - Mass Balance

$$\dot{m}_2 = \dot{m}_3$$
$$\dot{m}_5 = \dot{m}_6$$

  - Energy Balance
  - $\frac{dE_{cv}}{dt} = \sum_i m_i \left(h_i + \frac{{v_i}^2}{2} + gz_o\right) + \dot{Q} + \dot{W}$

$$\dot{Q} = \dot{m}(h_2 - h_3)$$
$$\dot{Q} = \dot{m}(h_5 - h_6)$$



Pumps

- Steady State
  - Mass Balance

$$\dot{m}_3 = \dot{m}_4$$
$$\dot{m}_8 = \dot{m}_5$$

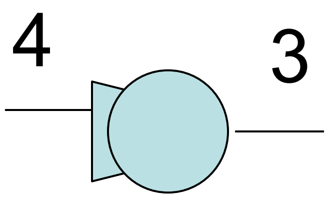
  - Energy Balance

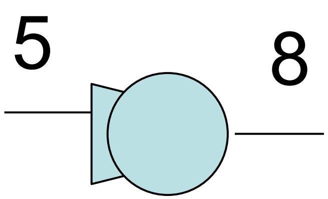
$$\dot{Q} = \dot{m}(\Delta h)$$

  - Entropy Balance

$\dot{m}_5 s_5 = \dot{m}_8 s_{8s}$ $\quad\quad$ $s_5 = s_{8s}$

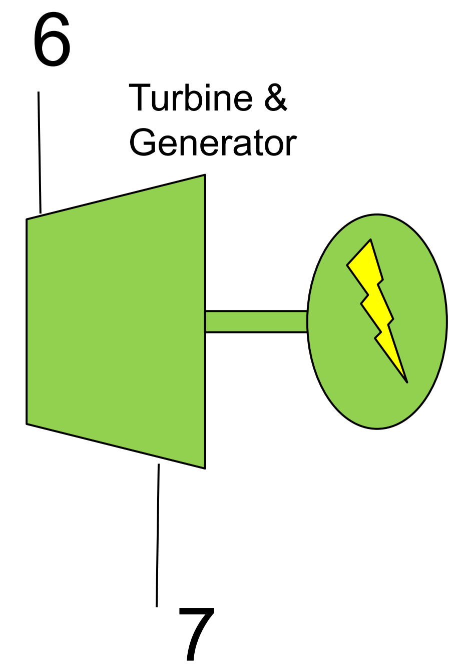
  - $\eta_p = \dfrac{h_{8s} - h_5}{h_8 - h_5}$





Turbine

- Steady State
  - Mass Balance
  - Energy Balance
  - Entropy Balance



$$\dot{m}_6 s_6 = \dot{m}_7 s_{7s} \qquad s_6 = s_{7s} \qquad x_{7s} = \frac{s_{7s} - s_f}{s_{fg}} \qquad h_{7s} = h_f + x_{7s} \cdot h_{fg}$$

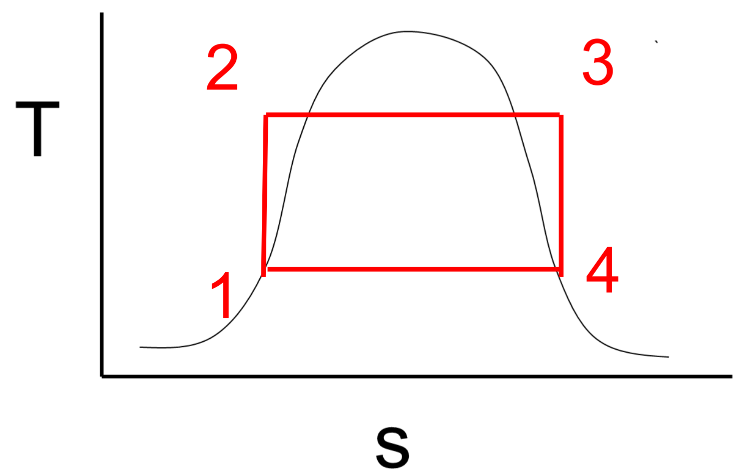
- $\eta_p = \dfrac{h_6 - h_7}{h_6 - h_{7s}}$

Steam Quality

- Measure of vapor content
  - 100% vapor is quality of 1, or x=1
  - $x = \frac{h-h_f}{h_{fg}} = \frac{s-s_f}{s_{fg}}$
- Given as condition of SG, or turbine
- Can be used as closure equation
- Significant role in derivation of 2 phase flow calculations

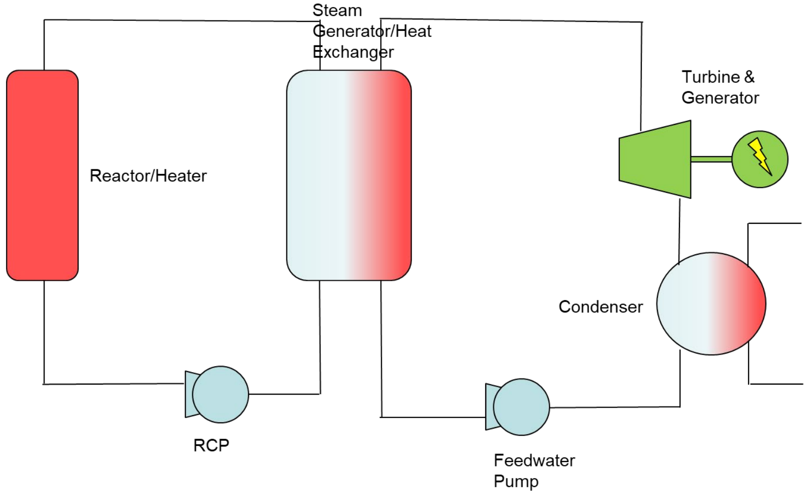
Thermodynamic Efficiency

- Net (common)
  - $\eta_T = \frac{\dot{W}_t + \dot{W}_p}{\dot{Q}}$
- Using T-S and cycle to right:
  - $\eta_{net} = \frac{(h_3 - h_4) - (h_2 - h_1)}{(h_3 - h_2)}$
  - $\eta_{net} = 1 - \frac{T_C}{T_H}$
    - (Must be in absolute!)



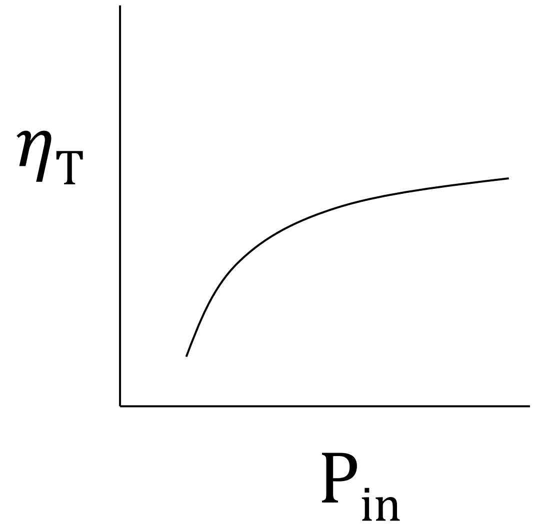
Simple Rankine Cycle

- Advantages:
  - Simplicity
  - Experience
- Disadvantages
  - Low efficiency
  - High Turbine Moisture
    - Erosion of blades
    - Bottoming cycle

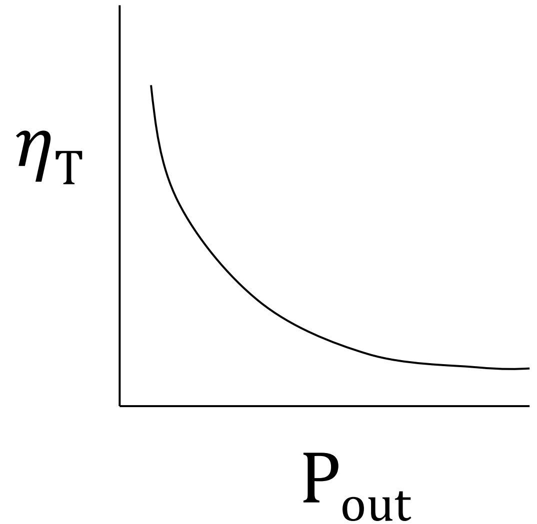


Efficiency Improvements

- Increase Turbine P_{in}



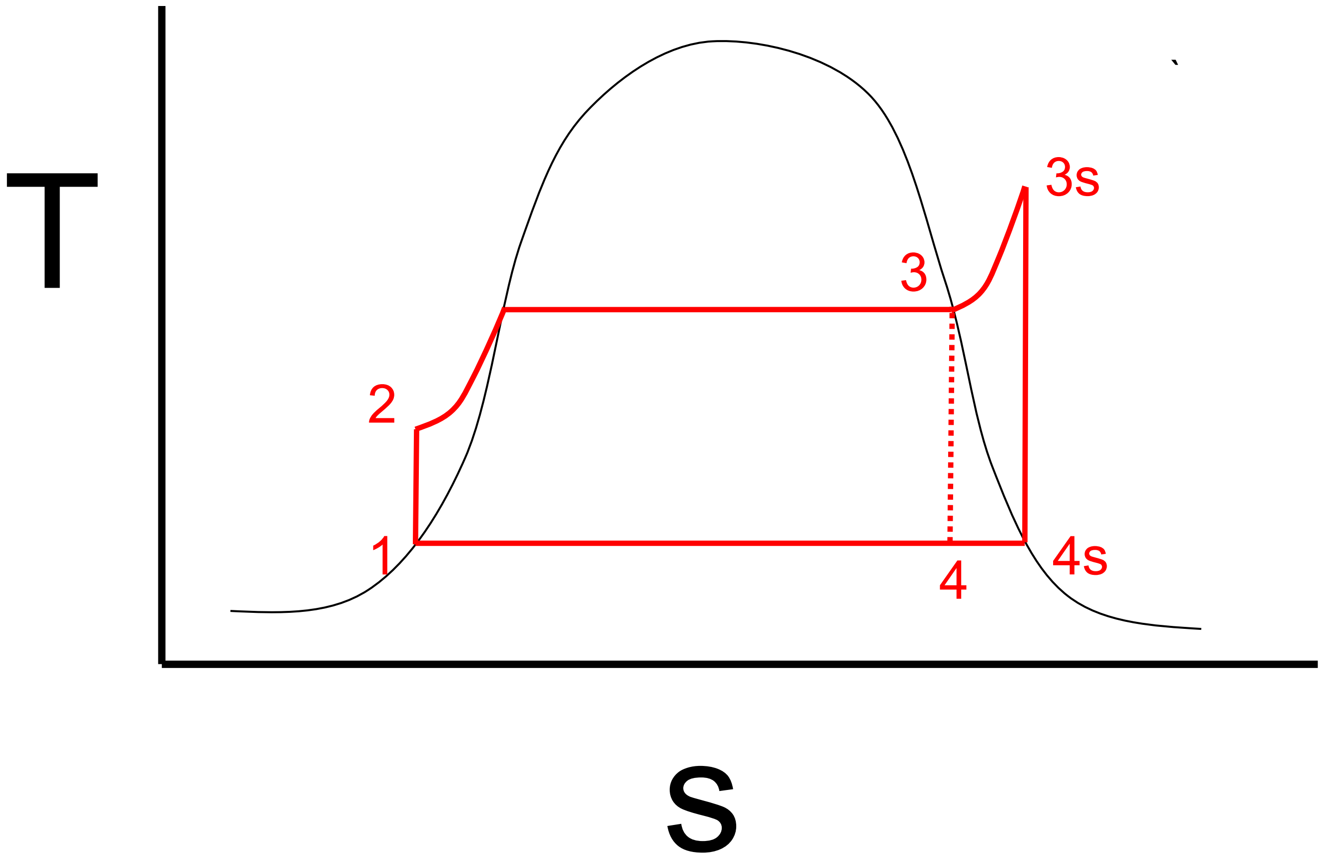
- Decrease Turbine P_{out}



- Several Methods

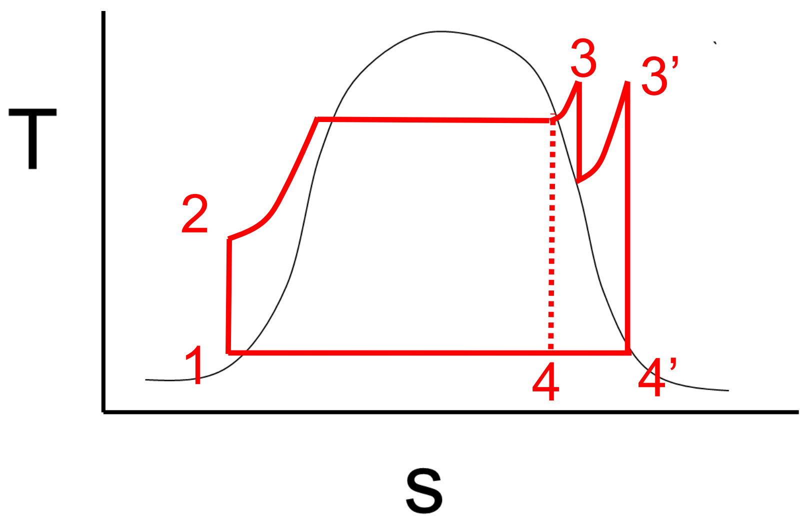
Superheating

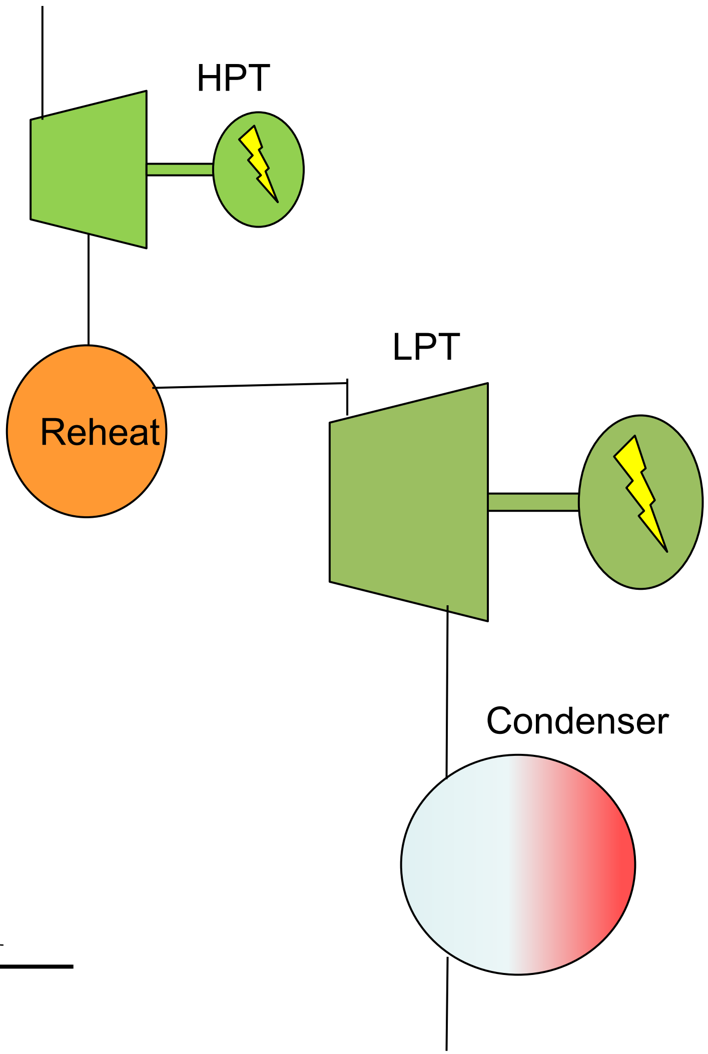
- Hurt if T_{max} limit



Reheating

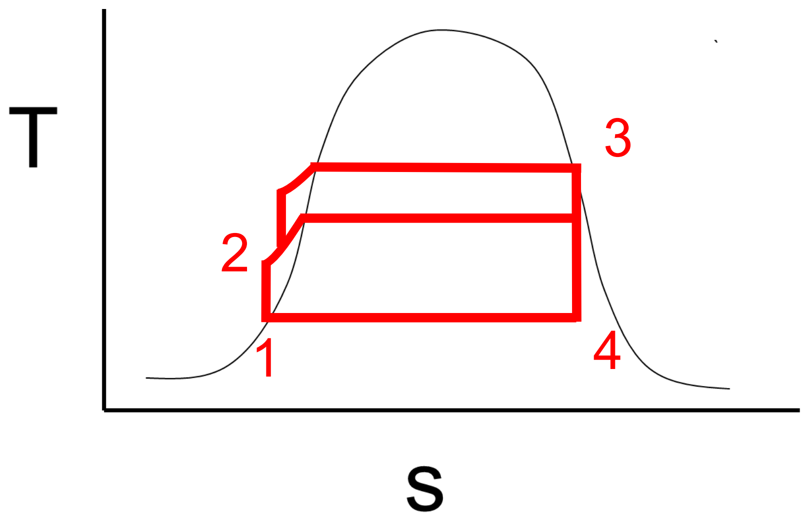
- Increase Quality
- Increase T-S area (work)
- η_T increase or decreases
  - Depends on P_{reheat}

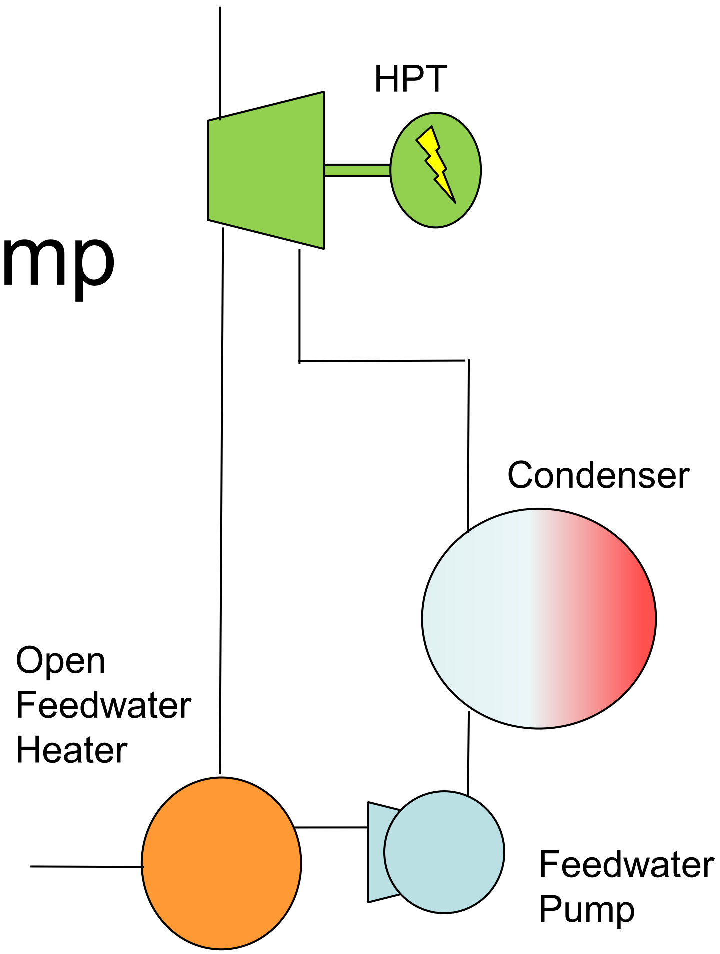




Regeneration

- "Preheat" fluid
- Increases average temp of heat addition
- η_T increases





Moisture Separation

- Remove condensate
- Improves x at T,P
- Additional Expansion
  - Improves η_T