Lecture 2.13

Methods for Improving Thermal Efficiency:
Superheating, Reheating, and Regeneration

Agenda

- Limitations of the Basic Rankine Cycle
- Thermodynamics of Superheating
- The Reheat Cycle and Exhaust Moisture Control
- Optimal Reheat Pressure
- Principles of Regenerative Feed Heating
- Open vs. Closed Feedwater Heaters
- Impact of Regeneration on Cycle Efficiency

Limitations of the Basic Rankine Cycle

- The ideal Rankine cycle operates with saturated steam at the turbine inlet.
- The lower mean temperature of heat addition (T_{m1}) inherently limits thermal efficiency ($\eta = 1 - T_2/T_{m1}$).
- Expansion deep into the two-phase region leads to high moisture content (dryness fraction $x < 0.88$) at the turbine exhaust.
- High moisture causes water droplets to impinge on low-pressure turbine blades at high velocities, leading to severe erosion and blade failure.

Principles of Increasing Efficiency

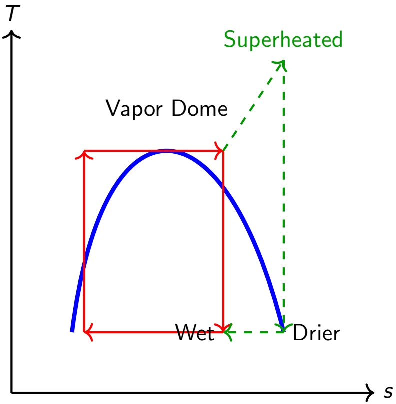
Efficiency Equation

$$\eta = 1 - \frac{T_{\text{reject}}}{T_{\text{add,mean}}}$$

- Following Carnot principles, efficiency increases if heat is added at a higher average temperature and rejected at a lower average temperature.
- Lowering condenser pressure (T_2) is practically limited by the ambient cooling water temperature and the difficulty of maintaining a high vacuum.
- Increasing boiler pressure raises T_{m1} but exacerbates the moisture problem at the turbine exhaust.
- **Practical engineering solutions** must therefore increase T_{m1} without producing excessive exhaust moisture: Superheating, Reheating, and Regeneration.

Superheating: Thermodynamic Concept

- Steam is heated beyond its saturation temperature at a constant boiler pressure before entering the turbine.
- The constant-pressure heat addition line extends into the superheated region on the T-s diagram.
- This process significantly increases the enthalpy of the steam at the turbine inlet ($h_3 > h_g$).
- By adding a substantial amount of heat at temperatures above the saturation temperature, the



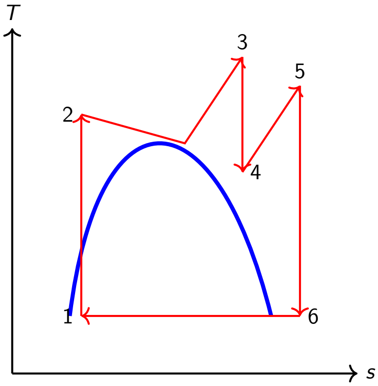
Superheating: Practical Implications

- Crucially, superheating shifts the isentropic expansion line to the right on the T-s diagram.
- This significantly reduces the moisture content at the turbine exhaust (increases dryness fraction, x_4), mitigating water droplet erosion.
- The maximum degree of superheating is bounded strictly by metallurgical constraints.
- Modern boiler tubes and high-pressure turbine blades typically limit superheat temperatures to approximately $600^{\circ}C - 620^{\circ}C$ using advanced austenitic steels.

Reheating: Concept and Necessity

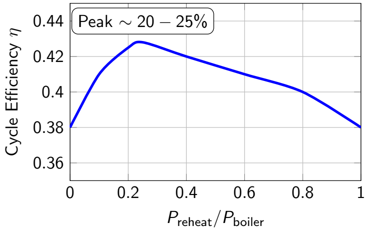
- To achieve higher efficiencies, modern plants use very high boiler pressures (subcritical up to 190 bar, supercritical > 221 bar).
- At these extreme pressures, even with maximum metallurgical superheating, the expansion would result in unacceptable moisture ($> 12\%$) at the exhaust.
- **Reheating solves this:** steam is expanded partially in a High-Pressure (HP) turbine.
- The steam is then extracted, routed back to the boiler reheater, heated at constant pressure, and finally expanded in an Intermediate/Low-Pressure (IP/LP) turbine.

- The T-s diagram illustrates two distinct expansion processes interrupted by an intermediate constant-pressure heating process.
- **Total Heat Added** $=$ $(h_3 - h_2)$ [Boiler] $+$ $(h_5 - h_4)$ [Reheater].
- **Total Turbine Work** $=$ $(h_3 - h_4)$ [HP] $+$ $(h_5 - h_6)$ [LP].
- While reheating increases network output, the cycle efficiency only improves if the mean temperature of heat addition during reheating exceeds the original cycle's T_1.



Reheating: Optimal Reheat Pressure

- Choosing the reheat pressure is critical; expanding too far before reheating negates efficiency gains.
- Analytical optimization reveals the optimal reheat pressure is typically 20% to 25% of the initial boiler pressure.
- Ultra-supercritical (USC) plants may employ double reheating to push efficiency further and manage moisture from even higher initial pressures (e.g., 300+ bar).
- Diminishing returns and the high capital cost of massive

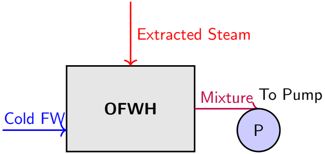


Regenerative Feed Heating: The Concept

- In a basic Rankine cycle, feedwater enters the boiler at a very low temperature (condenser temperature).
- Heating this cold water requires substantial heat addition at lower temperatures, severely depressing the overall mean temperature of heat addition.
- **Regeneration** involves extracting (bleeding) a fraction of steam from intermediate turbine stages to preheat the feedwater before it enters the boiler.
- This internal heat exchange approximates the ideal Carnot cycle heat addition process more closely, drastically improving efficiency.

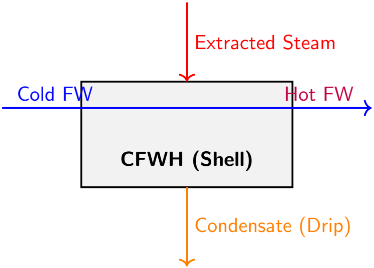
Open Feedwater Heaters (OFWH)

- Extracted steam mixes directly with the subcooled feedwater from the condenser in a mixing chamber.
- The ideal mixture leaves the heater as a saturated liquid exactly at the extraction pressure.
- Highly effective heat transfer (Terminal Temperature Difference $= 0$).
- **Disadvantage:** Requires a separate feedwater pump after each heater to raise the fluid pressure to the next stage or boiler pressure, increasing mechanical complexity.



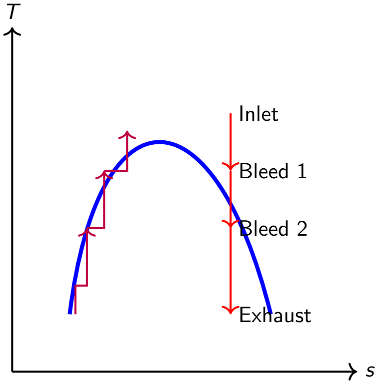
Closed Feedwater Heaters (CFWH)

- Extracted steam and feedwater do not mix; heat transfer occurs indirectly through a tube bundle (shell-and-tube heat exchanger).
- Feedwater passes through the tubes at high pressure, while extracted steam condenses on the shell side.
- The condensed steam (drip) is usually cascaded backward through a trap to a lower-pressure heater or the condenser.
- **Advantage:** Simpler pumping (requires only one main boiler feed pump).



Regeneration: T-s Diagram and Impact

- The T-s diagram for a regenerative cycle shows stepped heat addition as feedwater is progressively heated, raising T_{m1}.
- The mass flow rate in the turbine decreases after each extraction point ($m_1 > m_2 > m_3 \ldots$).
- While regeneration decreases both the total heat added in the boiler and the total turbine work output per kg of initial steam, the ratio (efficiency) increases significantly.
- **Secondary benefit:** Reduces the volume flow rate at the low-pressure turbine exhaust



Summary

Method	Primary Effect on Efficiency	Effect on Exhaust Moisture
Superheating	Increases (raises T_{m1})	Significantly Reduces
Reheating	Modest Increase	Significantly Reduces
Regeneration	Most Effective Increase (raises T_{m1})	Minor/No direct impact on x, but reduces volume

- **Superheating:** Increases cycle efficiency by raising T_{m1} and is crucial for reducing turbine exhaust moisture.
- **Reheating:** Primarily a mechanism to maintain acceptable exhaust dryness in high-pressure cycles.
- **Regeneration (Feedwater Heating):** The most effective method for increasing efficiency by raising T_{m1} through internal heat transfer.
- Modern thermal power plants utilize a combination of

Next Lecture Preview

- Solving complex Rankine cycle numerical problems.
- Calculating cycle efficiency with combined reheat and regenerative stages.
- Determining optimum extraction pressures for feedwater heaters.
- Energy balances for open and closed feedwater heaters.