Lecture 2.14

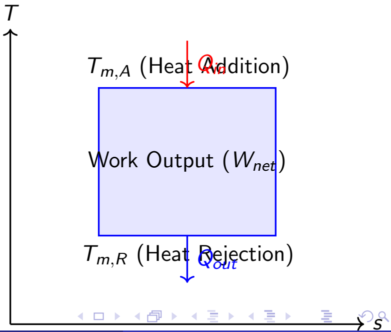
Methods for Improving Thermal Efficiency

Agenda

- Thermodynamic Basis for Efficiency Improvement
- Superheating of Steam: Concept and T-s Analysis
- Metallurgical Limits in Superheating
- Reheating Cycle: Mechanics and Benefits
- Optimal Reheat Pressure
- Regenerative Feed Water Heating
- Open vs. Closed Feedwater Heaters
- Combined Effects on Overall Efficiency

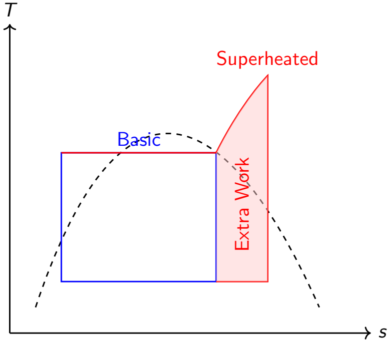
Thermodynamic Basis for Efficiency Improvement

- Carnot Principle: Efficiency is a function of mean temperature of heat addition ($T_{m,A}$) and mean temperature of heat rejection ($T_{m,R}$).
- Efficiency $\eta = 1 - (T_{m,R}/T_{m,A})$.
- To increase η: either decrease $T_{m,R}$ or increase $T_{m,A}$.
- Decreasing $T_{m,R}$ is limited by ambient conditions (cooling water temperature).
- Therefore, modern power cycles focus heavily on



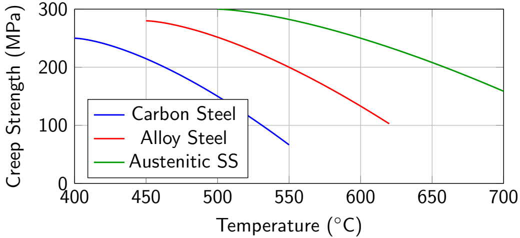
Superheating of Steam

- **Process:** Heating steam beyond its saturation point at constant pressure in the boiler's superheater.
- **Thermodynamic Effect:** Increases the mean temperature of heat addition ($T_{m,A}$) without increasing the boiler pressure.
- **Result:** Higher thermal efficiency for the cycle.
- **Moisture Content:** Superheating reduces the moisture content in steam at the turbine exhaust.
- Crucial for preventing



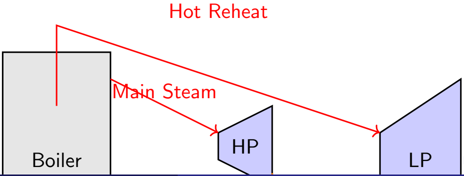
Metallurgical Constraints in Superheating

- Maximum temperature is fundamentally limited by the metallurgical properties of boiler tubes and turbine blades.
- Current practical limit is around 600°C – 620°C for ultra-supercritical plants using advanced alloys (e.g., creep-resistant steels, nickel-based superalloys).
- Exceeding this temperature leads to creep deformation, oxidation, and catastrophic failure of components under high stress.
- Economic balance: The cost of advanced alloys vs. the fuel savings from increased efficiency.



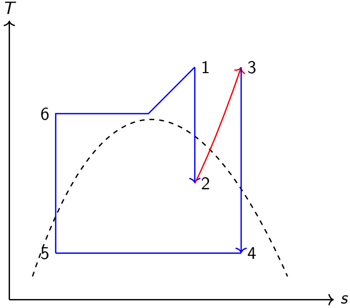
The Need for Reheating

- As boiler pressures increase to improve efficiency, expansion to condenser pressure results in unacceptable moisture levels ($> 10 - 12\%$) at turbine exhaust.
- Moisture causes severe erosion of the fast-moving low-pressure turbine blades.
- Solution: Reheating.
- Expand steam partially in a High-Pressure (HP) turbine.
- Route it back to the boiler to be reheated at constant pressure to a high temperature.
- Expand the reheated steam in Low-Pressure (LP) or Intermediate-Pressure (IP) turbines.



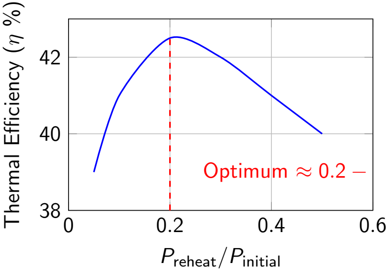
Thermodynamics of Reheating

- Reheating increases the total work output of the turbine (W_{net} increases).
- It also increases the total heat supplied (Q_{in} increases).
- Does it increase efficiency? Only if the mean temperature of heat addition during the reheat process is greater than the mean temperature of heat addition in the primary cycle.
- Primary purpose is often to control exhaust steam quality rather than purely a massive efficiency boost.
- Typically yields a $4 - 5\%$



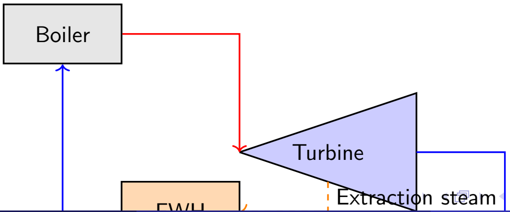
Optimal Reheat Pressure

- Choosing the pressure at which to extract steam for reheating is critical.
- If reheat pressure is too high, the gain in efficiency is minimal, and exhaust moisture might still be an issue.
- If reheat pressure is too low, the cycle efficiency can actually decrease below the non-reheat cycle.
- **Rule of thumb:** Optimum reheat pressure is generally 20% to 25% of the initial boiler pressure.



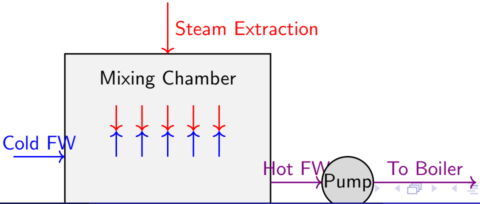
Regenerative Feed Water Heating

- **Problem:** In a basic Rankine cycle, sensible heat is added to cold feed water in the boiler, which happens at a very low temperature relative to the furnace.
- This low-temperature heat addition severely drops the mean temperature of heat addition ($T_{m,A}$).
- **Solution: Regeneration.**
- Extract a fraction of partially expanded steam from the turbine at various stages.
- Use this extracted steam to heat the boiler feed water before it enters the boiler.



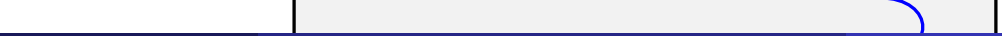
Open (Direct Contact) Feedwater Heaters

- **Mechanism:** Extracted steam directly mixes with the feed water.
- Heat transfer is highly efficient (terminal temperature difference is theoretically zero).
- Requires the extracted steam and feed water to be at the exact same pressure.
- Acts as a deaerator, removing dissolved gases (oxygen, carbon dioxide) from the feed water.
- Requires a separate feed pump after every open heater to step up the pressure for the next stage.



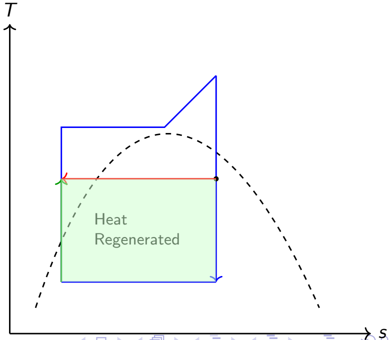
Closed Feedwater Heaters

- **Mechanism:** Shell-and-tube heat exchangers. Extracted steam condenses on the outside of tubes while feed water flows inside.
- No direct mixing; steam and feed water can be at different pressures.
- Only one main boiler feed pump is required, simplifying the fluid handling system.
- Less efficient heat transfer than open heaters due to thermal resistance of the tubes.
- Condensed extracted steam (drains) must be cascaded backward or pumped forward.



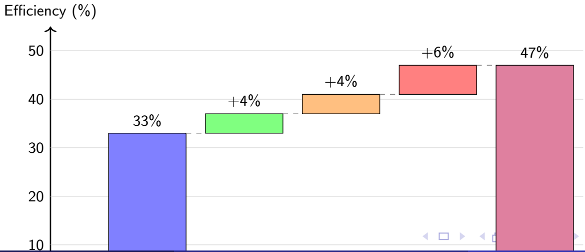
Impact of Regeneration on Cycle Performance

- Increases thermal efficiency by raising the mean temperature of heat addition.
- Reduces the heat supplied in the boiler (less fuel required per kg of steam).
- Reduces heat rejected to the condenser (smaller condenser size required).
- Reduces the mass flow rate of steam in the LP turbine stages, mitigating blade choking issues in very large capacity plants.
- **Drawback:** Decreases the



Summary: Synergistic Effects

- Modern subcritical and supercritical plants combine all three methods: superheating, reheating, and 5-8 stages of regenerative feed heating.
- Base Ideal Rankine Efficiency: $\sim 30 - 35\%$.
- With Superheating + Reheating + Regeneration: Practical efficiency reaches $40 - 45\%$.
- Ultra-supercritical plants (USC) push this closer to $47 - 48\%$.
- Every 1% increase in efficiency translates to millions of dollars in fuel savings and massive reductions in CO_2 emissions.



Next Lecture Preview

Topic: Boiler Systems and Combustion Mechanisms

- Types of modern high-pressure boilers (subcritical vs. supercritical).
- Draft systems (Forced, Induced, Balanced).
- Pulverized coal combustion technology.
- We will move from the thermodynamic cycle to the physical equipment that generates the steam.