Lecture 2.12

Rankine Cycle: Ideal & Actual

Agenda

- Introduction to Vapor Power Cycles
- The Ideal Rankine Cycle: Four Basic Processes
- T-s Diagram and Energy Analysis
- Deviations in the Actual Rankine Cycle
- Pump and Turbine Irreversibilities
- Isentropic Efficiencies
- Summary and Key Takeaways

Why the Rankine Cycle?

- The Carnot cycle is the most efficient, but highly impractical for vapor power systems due to two main reasons:
- 1. Isentropic compression of a two-phase liquid-vapor mixture is mechanically difficult and damages compressors/pumps.
- 2. Isothermal heat transfer in a single-phase region is impossible to achieve practically.
- The Rankine cycle overcomes these limitations by completely condensing the working fluid to a liquid before compression.
- This allows the use of a simple liquid pump instead of a two-phase compressor, significantly reducing back-work ratio.

Ideal Rankine Cycle: Components & Processes

- The ideal Rankine cycle consists of four internally reversible processes:
- Process 1-2: Isentropic compression in a pump. Saturated liquid water is compressed to the boiler operating pressure.
- Process 2-3: Constant pressure heat addition in a boiler. Water is heated to saturation and boiled into superheated vapor.
- Process 3-4: Isentropic expansion in a turbine. High-pressure steam expands, generating mechanical work.
- Process 4-1: Constant pressure heat rejection in a condenser. Steam is condensed back to saturated liquid.

T-s Diagram of the Ideal Rankine Cycle

- The Temperature-Entropy (T-s) diagram visually represents the thermal energy transfers.
- Area under curve 2-3 represents total heat added (q_in).
- Area under curve 4-1 represents total heat rejected (q_out).
- The enclosed area (1-2-3-4) represents the net work output (w_net = q_in - q_out).

Energy Analysis: The Pump and Boiler

- Applying the Steady-Flow Energy Equation (SFEE) to each component (assuming kinetic and potential energy changes are negligible).
- Pump Work (w_p,in): w_p,in = h2 - h1. Since the fluid is an incompressible liquid, w_p,in \ensuremath{\approx} v1(P2 - P1), where v1 is specific volume at state 1.
- State 2 Enthalpy: h2 = h1 + w_p,in.
- Boiler Heat Input (q_in): q_in = h3 - h2. This is the thermal energy transferred from the combustion gases to the working fluid.

Energy Analysis: Turbine and Condenser

- Turbine Work (w_t,out): w_t,out = h3 - h4. This represents the gross mechanical work produced by the expansion of steam.
- Condenser Heat Rejection (q_out): q_out = h4 - h1. This heat is transferred to the cooling water (e.g., from a cooling tower or river).
- Net Work Output (w_net): w_net = w_t,out - w_p,in. Alternatively, w_net = q_in - q_out.

Thermal Efficiency of Ideal Rankine Cycle

- Thermal efficiency (\ensuremath{\eta}_th) defines how effectively heat is converted to work.
- \ensuremath{\eta}_th = w_net / q_in = (w_t,out - w_p,in) / q_in
- \ensuremath{\eta}_th = 1 - (q_out / q_in) = 1 - (h4 - h1) / (h3 - h2)
- To increase efficiency: Increase average temperature of heat addition (superheating, high boiler pressure) or decrease temperature of heat rejection (lower condenser pressure).

The Actual Rankine Cycle: Irreversibilities

- Real cycles deviate from the ideal due to internal and external irreversibilities.
- Fluid Friction: Causes pressure drops in the boiler, condenser, and the connecting piping. Boiler pressure drops require the pump to operate at a higher discharge pressure.
- Heat Loss: Thermal energy is lost to the surroundings from the boiler, turbine, and piping, requiring more fuel to maintain required heat input (q_in).
- Component Inefficiencies: The pump and turbine are not perfectly isentropic; they generate entropy.

Isentropic Efficiencies: Turbine and Pump

- Turbine Isentropic Efficiency (\ensuremath{\eta}_t): The ratio of actual turbine work to ideal (isentropic) turbine work.
- \ensuremath{\eta}_t = Actual Work / Isentropic Work = (h3 - h4a) / (h3 - h4s)
- Pump Isentropic Efficiency (\ensuremath{\eta}_p): The ratio of ideal pump work to actual pump work required.
- \ensuremath{\eta}_p = Isentropic Work / Actual Work = (h2s - h1) / (h2a - h1)
- Where 'a' denotes the actual state and 's' denotes the isentropic state.

T-s Diagram: Ideal vs. Actual Cycle

- The actual expansion (3-4a) and compression (1-2a) processes show an increase in entropy (shift to the right on the T-s diagram).
- State 4a has a higher enthalpy than 4s, meaning less work was extracted.
- State 4a also typically has a higher steam quality (x) than 4s, which is slightly beneficial for preventing turbine blade erosion.
- State 2a requires a higher enthalpy input from the pump than 2s.

Impact on Cycle Performance

- Actual thermal efficiency: \ensuremath{\eta}_th,actual = (w_t,actual - w_p,actual) / q_in,actual
- Increased heat rejection: The condenser must reject more heat (h4a - h1) than in the ideal case (h4s - h1).
- Increased fuel consumption: Lower net work output per kg of steam means a higher mass flow rate of steam is needed for a given power output, increasing the fuel requirement.
- Maintenance considerations: Real components wear out, further decreasing \ensuremath{\eta}_t and \ensuremath{\eta}_p over the plant's lifetime.

Summary

- The Rankine cycle is the fundamental thermodynamic model for steam power plants, overcoming Carnot's practical limitations.
- The ideal cycle consists of isentropic pumping, isobaric heat addition, isentropic expansion, and isobaric heat rejection.
- Thermal efficiency depends on the ratio of net work to heat input.
- Actual cycles deviate due to fluid friction and non-isentropic behavior in pumps and turbines, reducing overall efficiency and work output.

Next Lecture Preview

- Topic 2.2: Reheat and Regenerative Rankine Cycles
- We will explore how to modify the simple Rankine cycle to increase efficiency.
- Reheating steam to prevent excessive moisture in the low-pressure turbine.
- Regeneration (feedwater heating) to increase the average temperature of heat addition.