Lecture 2.11

Rankine Cycle: Ideal and Actual Cycles

Agenda

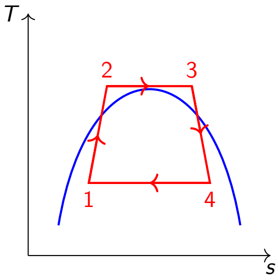
- Limitations of the Carnot Vapor Cycle
- Components and Processes of the Ideal Rankine Cycle
- Thermodynamic Analysis of Ideal Components
- Cycle Performance Metrics (Thermal Efficiency, Work Ratio)
- Deviations in the Actual Rankine Cycle
- Isentropic Efficiencies of Turbines and Pumps
- T-s Diagrams for Ideal vs. Actual Cycles

Limitations of the Carnot Vapor Cycle

Theoretical Maximum vs. Practicality

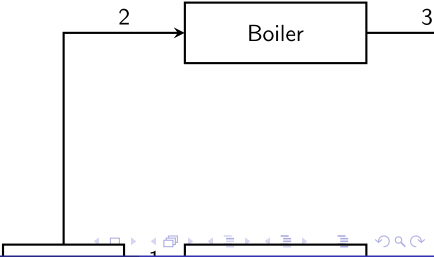
The Carnot cycle represents the maximum theoretical efficiency between two temperature limits, but poses practical challenges for vapor power.

- **Compression:** Compression of a two-phase mixture (liquid + vapor) to a saturated liquid in a compressor is practically difficult to design and highly inefficient.
- **Heat Addition:** Limited to the saturation dome if it must remain isothermal, severely restricting the maximum cycle temperature and preventing superheating.



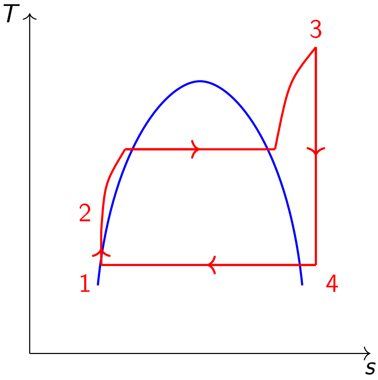
Basic Components of the Rankine Cycle

- **Boiler (Steam Generator):** Reversible constant pressure heat addition. Converts compressed subcooled liquid into superheated or saturated steam.
- **Turbine:** Reversible adiabatic (isentropic) expansion. Steam expands, turning the rotor and generating shaft work, dropping in pressure and temperature.
- **Condenser:** Reversible constant pressure heat rejection. Exhaust steam



The Ideal Rankine Cycle - T-s Diagram

- **Process 1-2:** Isentropic compression in pump. State 1 is saturated liquid at condenser pressure; State 2 is compressed liquid at boiler pressure.
- **Process 2-3:** Constant pressure heat addition in boiler. Water is heated to saturation, boiled, and often superheated (State 3).
- **Process 3-4:** Isentropic expansion in turbine. Steam expands to condenser pressure (State 4), entering the two-phase region.



Thermodynamic Analysis: Pump and Boiler

Steady Flow Energy Equation (SFEE)

Applying the Steady Flow Energy Equation (SFEE) and assuming negligible changes in kinetic and potential energy.

- **Pump Work (W_p):** Since process 1-2 is isentropic and fluid is incompressible,

$$W_p = h_2 - h_1 = v_1(P_2 - P_1)$$

  where v_1 is specific volume of saturated liquid.
- **Boiler Heat Addition (Q_{in}):** Constant pressure heating, meaning

$$Q_{\text{in}} = h_3 - h_2$$

- **Approximation:** The enthalpy of compressed liquid h_2 can be approximated as $h_2 \approx h_1 + v_1(P_2 - P_1)$ if compressed liquid tables are unavailable.

Thermodynamic Analysis: Turbine and Condenser

- **Turbine Work (W_t):** Isentropic expansion through the turbine yields positive work output.

$$W_t = h_3 - h_4$$

- **Condenser Heat Rejection (Q_{out}):** The steam rejects heat at constant pressure to the cooling water.

$$Q_{\text{out}} = h_4 - h_1$$

- **Net Work Output (W_{net}):** The total useful work from the cycle is

$$W_{\text{net}} = W_t - W_p$$

State 4 Enthalpy

State 4 enthalpy (h_4) is determined using the quality of steam (x_4) at the condenser pressure: $h_4 = h_f + x_4(h_{fg})$.

Cycle Performance Metrics

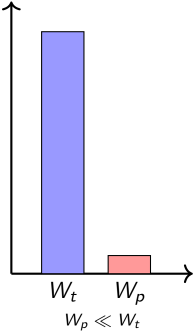
- **Thermal Efficiency (η_{th}):** The ratio of net work output to total heat input.

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{W_t - W_p}{h_3 - h_2} = 1 - \frac{Q_{out}}{Q_{in}}$$

- **Work Ratio:** Defined as Net Work divided by Positive Work. Work Ratio $= \frac{W_{net}}{W_t}$. In Rankine cycles, this is very close to 1 because W_p is very small compared to W_t.
- **Specific Steam Consumption (SSC):** The mass flow rate of steam required to produce 1 kW of net power.

$$\text{SSC} = \frac{3600}{W_{net}} \text{ (in kg/kWh)}$$

A lower SSC indicates a more compact



The Actual Rankine Cycle: Sources of Irreversibility

Real-World Deviations

Real-world power plants do not operate ideally. Irreversibilities exist in all components, reducing net work and efficiency.

Internal Irreversibilities

- Fluid friction in pipes, boiler tubes, and turbine blades causes pressure drops and entropy generation.

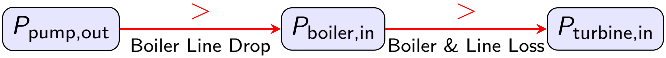
External Irreversibilities

- Heat loss from the boiler, turbine casing, and piping to the surrounding environment.

Consequently, expansion in the turbine and compression in the pump are neither isentropic nor adiabatic in reality.

Piping and Component Pressure Drops

- **Boiler Pressure Drop:** To maintain flow, steam exits the boiler at a lower pressure than the feedwater entering it.
- **Line Pressure Drop:** Friction in the pipe connecting the boiler to the turbine causes a pressure loss and potential heat loss (temperature drop).
- **Condenser Pressure Drop:** The condenser pressure at the turbine exhaust is higher than the pressure at the pump inlet.
- **Impact:** The feedwater pump must discharge at a pressure significantly higher than the nominal turbine inlet pressure to overcome these losses.



Isentropic Efficiencies of Pump and Turbine

To account for internal irreversibilities in rotating machinery, we use isentropic efficiencies.

Turbine Isentropic Efficiency (η_t)

The ratio of actual turbine work to ideal (isentropic) turbine work.

$$\eta_t = \frac{h_3 - h_{4,\text{actual}}}{h_3 - h_{4,\text{ideal}}} \implies W_{t,\text{actual}} = \eta_t (h_3 - h_{4,\text{ideal}})$$

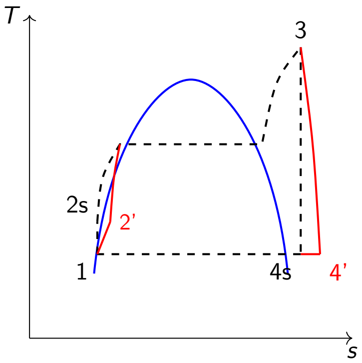
Pump Isentropic Efficiency (η_p)

The ratio of ideal (isentropic) pump work to actual pump work.

$$\eta_p = \frac{h_{2,\text{ideal}} - h_1}{h_{2,\text{actual}} - h_1} \implies W_{p,\text{actual}} = \frac{h_{2,\text{ideal}} - h_1}{\eta_p}$$

T-s Diagram of the Actual Rankine Cycle

- The expansion process (3 to 4') curves to the right, showing an increase in entropy ($s_{4'} > s_3$) due to friction in the turbine.
- The compression process (1 to 2') also curves to the right ($s_{2'} > s_1$) due to friction in the pump.
- Actual net work area is visually smaller than the ideal cycle area.
- Notice the steam quality at actual turbine exhaust ($x_{4'}$) is higher (drier) than the ideal exhaust (x_{4s}), slightly reducing moisture erosion.



Summary

- The Rankine cycle is the practical standard for vapor power generation, overcoming Carnot cycle limitations by condensing steam to a pumpable liquid.
- Ideal cycle analysis relies on isentropic assumptions for pumps and turbines, and isobaric assumptions for heat exchangers.
- Cycle thermal efficiency depends heavily on maximizing the mean temperature of heat addition and minimizing heat rejection temperature.
- Actual cycles suffer from fluid friction and heat losses, modeled using turbine and pump isentropic efficiencies, which decrease net work and overall efficiency.

Preview of Next Lecture

Pushing the Limits of Efficiency

How can we improve the efficiency of the basic Rankine cycle? Next time, we will explore modifications to the Rankine cycle: Reheating and Regeneration.

- **Reheat Cycle:** Expanding steam in stages and returning it to the boiler to increase average heat addition temperature and reduce exhaust moisture.
- **Regenerative Cycle:** Using turbine extraction steam to preheat feedwater, dramatically improving cycle efficiency.