Lecture 8 Steam Cycles in Thermal Plants: Rankine Cycle and its Modifications

Goal of the lecture: To study the Rankine steam cycle as the fundamental thermodynamic cycle of thermal power plants and to analyze its main modifications aimed at improving efficiency and performance.

Brief lecture notes: This lecture presents the Rankine cycle as the principal operating cycle for steam power plants, explaining its thermodynamic basis, components, and performance evaluation. The discussion extends to common modifications — including the reheat cycle, regenerative feedwater heating, and supercritical cycles — that enhance thermal efficiency and reduce fuel consumption. The analysis emphasizes energy and exergy perspectives, showing how improvements in cycle design can significantly increase power generation efficiency.

Main part

The Rankine cycle is the idealized thermodynamic cycle used to describe the operation of steam power plants, in which water is used as the working fluid. It converts heat energy from fuel combustion or another heat source into mechanical work and, subsequently, electricity.

The cycle consists of four main processes:

1. Isentropic compression in a pump (liquid water is pressurized).
2. Constant-pressure heat addition in a boiler (water is vaporized to steam).
3. Isentropic expansion in a turbine (steam performs work).
4. Constant-pressure heat rejection in a condenser (steam condenses back to liquid).

The ideal Rankine cycle assumes reversible adiabatic (isentropic) expansion and compression with no friction or losses.

Energy Balance and Efficiency

The energy balance of the Rankine cycle is based on the First Law of Thermodynamics. The thermal efficiency is given by:

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{(h_3 - h_4) - (h_2 - h_1)}{h_3 - h_2}$$

where h_1, h_2, h_3, h_4 are the specific enthalpies at the respective states (pump inlet, pump outlet, turbine inlet, turbine outlet).

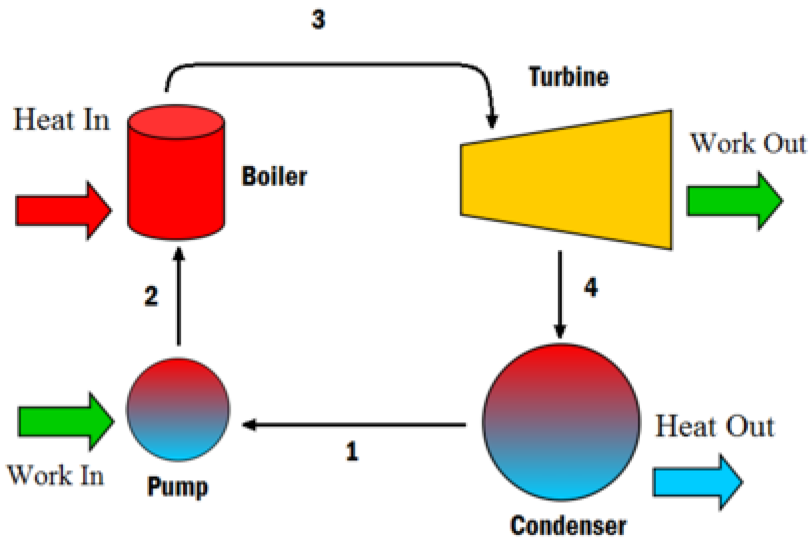
The work and heat terms are defined as:

- Pump work: $W_p = h_2 - h_1$
- Turbine work: $W_t = h_3 - h_4$
- Heat added: $Q_{in} = h_3 - h_2$
- Heat rejected: $Q_{out} = h_4 - h_1$

The net work is the difference between turbine and pump work, and the efficiency depends primarily on the pressure ratio and temperature difference between the boiler and the condenser.

T–s Diagram of the Rankine Cycle

Figure 1. Ideal Rankine Cycle on a Temperature–Entropy (T–s) diagram.



Rankine Cycle

This figure 1 illustrates how the working fluid changes phase and energy state throughout the cycle — from liquid water to superheated steam and back.

The Rankine cycle can be improved through several key modifications, each designed to enhance performance and efficiency. The reheat cycle reduces steam moisture and increases the average temperature of heat addition, leading to an efficiency improvement of about 3–5%. The regenerative cycle utilizes extracted steam to preheat the feedwater entering the boiler, thereby reducing fuel consumption and increasing efficiency by approximately 4–8%. The supercritical cycle, operating above the critical pressure of water (22.1 MPa), achieves a smoother phase transition and higher thermodynamic efficiency, typically improving performance by 10–15%. Finally, the combined heat and power (CHP) configuration captures and reuses waste heat for district heating or industrial applications, resulting in significantly higher overall energy utilization compared to conventional power plants.

5. Modifications of the Rankine Cycle

The Reheat Rankine Cycle

In the reheat cycle, steam expands partially in a high-pressure turbine, is reheated in the boiler, and then expands again in a low-pressure turbine. This prevents excessive moisture at the turbine exit and improves work output. The cycle efficiency becomes:

$$\eta_{reheat} = \frac{(h_3 - h_4) + (h_5 - h_6) - (h_2 - h_1)}{(h_3 - h_2) + (h_5 - h_4)}$$

Reheating is particularly effective in large power plants, where higher pressures and temperatures are feasible.

Regenerative Feedwater Heating

The regenerative Rankine cycle increases efficiency by preheating the feedwater with steam extracted from intermediate turbine stages. This process raises the average temperature at which heat is added, thereby reducing

fuel consumption.
Modern plants often employ 6–8 feedwater heaters to achieve optimal performance.

Supercritical and Ultra-Supercritical Cycles

At pressures above the critical point of water (22.1 MPa), there is no distinct phase change. The supercritical Rankine cycle operates entirely in the fluid phase, allowing much higher boiler temperatures and reduced irreversibility. Typical efficiency improvements are 10–15% compared with conventional subcritical cycles.
Ultra-supercritical plants (above 25 MPa and 600°C) represent the most advanced designs in commercial operation.

Performance Comparison

Cycle Type	Boiler Pressure (MPa)	Max Temp (°C)	Typical Efficiency (%)
Simple Rankine	10	500	33–36
Reheat	15	540	37–40
Regenerative	16	540	38–42
Supercritical	24	580	42–45
Ultra-supercritical	25+	600–620	45–48

Such improvements show how thermodynamic refinements directly translate to fuel savings and reduced CO_2 emissions.

Engineering Significance

The Rankine cycle remains the cornerstone of global electricity generation. Over 70% of thermal power plants operate based on its principles. Continuous innovations — such as reheat, regenerative, and supercritical configurations — are driven by the pursuit of higher efficiency and lower environmental impact. Understanding the thermodynamic basis of these cycles enables engineers to design and operate more efficient, cleaner, and economically viable power systems.

Questions for Self-Control

1. What are the main processes in the Rankine cycle?
2. How is the thermal efficiency of the Rankine cycle calculated?
3. What are the benefits of the reheat and regenerative modifications?
4. Why do supercritical cycles achieve higher efficiencies?
5. How does moisture content affect turbine performance?

Literature

1. Çengel, Y. A., & Boles, M. A. *Thermodynamics: An Engineering Approach.* McGraw-Hill, 2019.
2. Moran, M. J., Shapiro, H. N. *Fundamentals of Engineering Thermodynamics.* Wiley, 2020.
3. Bejan, A. *Advanced Engineering Thermodynamics.* Wiley, 2016.
4. El-Wakil, M. M. *Powerplant Technology.* McGraw-Hill, 1984.
5. Nag, P. K. *Power Plant Engineering.* McGraw-Hill Education, 2017.