Aadi Chhajed
Roll No.: 240004

Assignment 2: Theory of Rankine and Brayton Cycles

Thermodynamic Power Cycles

1. Introduction

Thermodynamic power cycles are important because they explain how we convert energy from fuels, heat, or natural sources into useful work like electricity. They show how heat flows through engines, turbines, and power plants, and help us understand where energy is used efficiently and where it is wasted. By studying these cycles, engineers can design systems that produce more power using less fuel, reduce losses, and lower pollution. In simple terms, thermodynamic power cycles help us turn raw energy into usable energy in the most practical and economical way.

Rankine Cycle

In this cycle, water is heated in a boiler to produce high-pressure steam, which then expands through a turbine to produce mechanical work. After doing work, the steam is condensed back into water in a condenser and pumped again to the boiler, completing the cycle. The Rankine cycle is important because it efficiently converts heat energy into mechanical and electrical energy and forms the basic working principle of most thermal power stations around the world.

Brayton Cycle

In this cycle, air is first compressed, then heated at constant pressure by burning fuel, and finally expanded through a turbine to produce work. Part of the turbine work runs the compressor, and the remaining power is used for useful output like electricity or thrust.

2. Rankine Cycle

2.1. Description of the Ideal Rankine Cycle

Water enters the pump at state 1 as saturated liquid and is compressed isentropically to the operating pressure of the boiler. The water temperature increases somewhat during this isentropic compression process due to a slight decrease in the specific volume of water. The vertical distance between states 1 and 2 on the T-s diagram is greatly exaggerated for clarity. Water enters the boiler as a compressed liquid at state 2 and leaves as a superheated vapor at state 3. The boiler is basically a large heat exchanger where the heat originating from combustion gases, nuclear reactors, or other sources is transferred to the water essentially at constant pressure. The boiler, together with the section where the steam is superheated (the super-heater), is often called the steam generator. The superheated vapor at state 3 enters the turbine, where it expands isentropically and produces work by rotating the shaft connected to an electric generator. The pressure and the temperature of steam drop during this process to the values at state 4, where steam enters the condenser. At this state, steam is usually a saturated liquid–vapor mixture with a high quality. Steam is condensed at constant pressure in the condenser, which is basically a large heat exchanger, by rejecting heat to a cooling medium such as a lake, a river, or the atmosphere. Steam leaves the condenser as saturated liquid and enters the pump, completing the cycle. In areas where water is precious, the power plants are cooled by air instead of water.

2.2. Major Components

- Boiler: It adds heat to convert water into steam at high pressure.
- Turbine: Converts steam energy into mechanical work.
- Condenser: Removes heat and converts steam back into liquid water.
- Pump: Raises the pressure of the condensed water and sends it back to the boiler.

2.3. Temperature–Entropy (T–s) Diagram

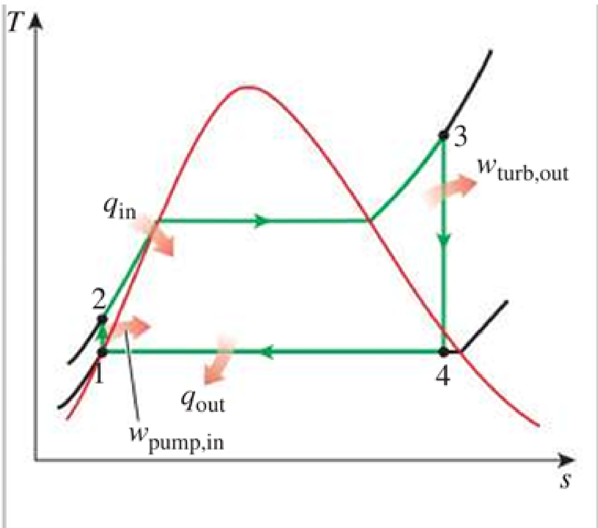

FIGURE 10–2
The simple ideal Rankine cycle.

Figure 1: Simple Rankine cycle on the T–s diagram

2.4. Thermal Efficiency

$$\eta_{th} = \frac{W_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} \tag{1}$$

$$W_{net} = q_{in} - q_{out} = W_{turb,out} - W_{pump,in} \tag{2}$$

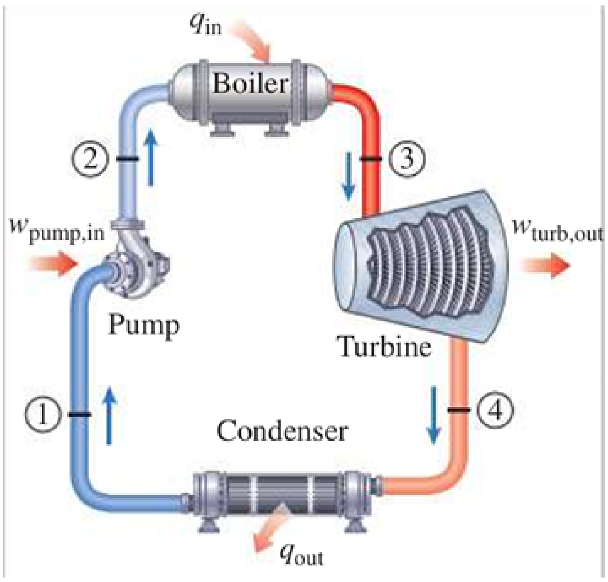

Figure 2: Boiler, turbine, condenser, and pump in the Rankine cycle

3. Brayton Cycle

3.1. Description of the Ideal Brayton Cycle

The Brayton cycle is the ideal thermodynamic cycle for gas-turbine engines. It was originally proposed by George Brayton and is widely used today in aircraft propulsion and gas-turbine power plants. Gas turbines usually operate on an open cycle, where air is taken from the atmosphere, fuel is burned, and exhaust gases are discharged. This open cycle is originally modeled as a closed cycle using the air-standard assumptions, leading to the ideal Brayton cycle. The cycle consists of four internally reversible processes executed in steady-flow devices.

3.2. Four Basic Processes

1) **1–2 Isentropic Compression (Compressor):** Air is compressed from a low pressure to a high pressure in the compressor. During this process, both pressure and temperature increase while entropy remains constant.

2) **2–3 Constant-Pressure Heat Addition (Combustion Chamber / Heat Exchanger):** Heat is added to the compressed air at constant pressure, resulting in a significant rise in temperature.

3) **3–4 Isentropic Expansion (Turbine):** The high-temperature & pressure gas expands through the turbine and produce work. Pressure and temperature decrease while entropy remains constant.

4) **4–1 Constant-Pressure Heat Rejection:** Heat is rejected at constant pressure to the surroundings, and the working fluid returns to its initial state.

3.3. Major Components

- Compressor: Raises the pressure and temperature of the incoming air.

- Combustion Chamber : Adds heat at constant pressure by burning fuel.

- Turbine: Extracts work from the high-temperature gases to drive the compressor and produce net power.

3.4. Temperature–Entropy (T–s) Diagram

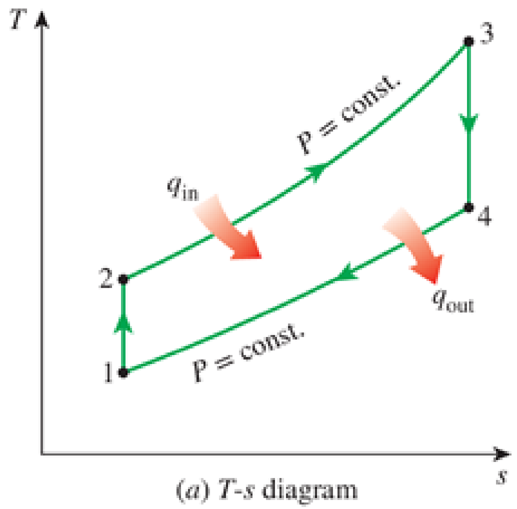

Figure 3: Ideal Brayton cycle on the T–s diagram

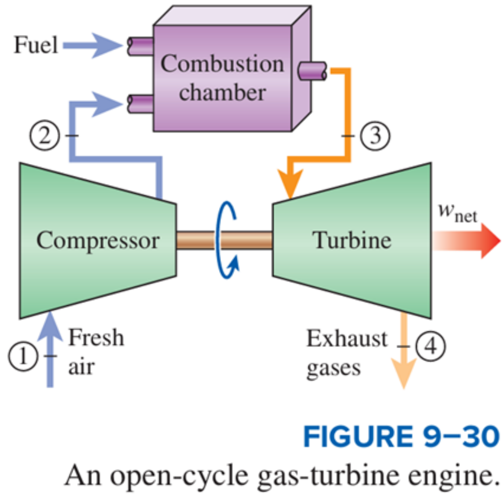

Figure 4: Compression, combustion chamber, and turbine arrangement in the Brayton cycle

3.5. Thermal Efficiency

$$\eta_{\text{th,Brayton}} = 1 - \frac{c_p\,(T_4 - T_1)}{c_p\,(T_3 - T_2)} = 1 - \frac{T_4 - T_1}{T_3 - T_2} \tag{3}$$

4. Comparison

The Rankine cycle uses water or steam as the working fluid, while the Brayton cycle operates using air or gas.

In the Rankine cycle, energy conversion takes place through a boiler, turbine, condenser, and pump, whereas the Brayton cycle uses a compressor, combustion chamber, and turbine.

Compression in the Rankine cycle requires very little work because the fluid is in liquid form, but the Brayton cycle needs much higher compression work since a gas is being compressed.

The Rankine cycle is mainly used in large thermal and nuclear power plants, while the Brayton cycle is commonly used in gas turbines and aircraft engines.

5. Conclusion

Both the Rankine and Brayton cycles play an important role in power generation, but they are used for different purposes. The Rankine cycle is more suitable for large-scale, steady power plants where steam is used to produce electricity efficiently. The Brayton cycle is preferred for applications that require compact systems, quick start-up, and high power-to-weight ratio, such as gas turbines and aircraft engines. Understanding these ideal cycles helps in analyzing real systems, identifying losses, and improving the overall performance and efficiency of power plants.

References

- Cengel, Y. A., & Boles, M. A., *Thermodynamics: An Engineering Approach.*