Assignment 2: Theory of Rankine and Brayton Cycles

Introduction

Thermodynamic power cycles are essential for energy conversion as they provide a systematic way to convert heat energy into useful work and electrical power. These cycles form the basis of operation for engines and power plants used in power generation and transportation.

- Power cycles allow engines and power plants to operate continuously by returning the working fluid, such as steam or air, to its initial state after each cycle.
- The performance of a power plant depends largely on the type of cycle used and the conditions under which it operates. Studying ideal cycles helps in understanding real power plants and identifying their limitations.
- The Otto and Diesel cycles are commonly used in internal combustion engines for transportation.

Among the various power cycles, the Rankine cycle and the Brayton cycle are widely used in practical applications. The Rankine cycle is mainly used in steam power plants, where water is the working fluid and undergoes phase change from liquid to vapor and back to liquid. The Brayton cycle, on the other hand, is used in gas turbine power plants and jet engines. In this cycle, the working fluid remains in the gaseous state throughout the process.

Rankine Cycle

The Rankine cycle is the basic thermodynamic cycle used in steam power plants. In this, water is used as the working fluid and it undergoes phase change during the operation.

The Rankine cycle operates as a closed cycle, meaning that the same working fluid is continuously reused. It consists of four main processes that take place in four major components: the pump, boiler, turbine, and condenser. To simplify analysis, the ideal Rankine cycle assumes that all processes occur without internal irreversibilities.

The ideal Rankine cycle consists of the following four thermodynamic processes:

- **Process 1–2: Isentropic compression in the pump**
  In this, water enters the pump as a saturated liquid at state 1 and is compressed isentropically to the boiler pressure. Because the working fluid is in liquid form, the pump requires only a small amount of work. The temperature of water increases slightly during compression. On the T–s diagram, this process is shown as a nearly vertical line, which is often exaggerated for clarity.

- **Process 2–3: Constant-pressure heat addition in the boiler**
  In this, the compressed liquid water enters the boiler, where heat is added at almost constant pressure. As heat is supplied, the water is converted into steam and may become superheated before leaving the boiler at state 3. The boiler functions as a large heat exchanger that transfers heat from sources such as combustion gases or nuclear reactors.

- **Process 3–4: Isentropic expansion in the turbine**
  In this, the superheated steam expands isentropically through the turbine and produces mechanical work. During expansion, the pressure and temperature of the steam decrease, and at the turbine exit, the steam is usually a high-quality liquid–vapor mixture.

- **Process 4–1: Constant-pressure heat rejection in the condenser**
  In this, the low-pressure steam enters the condenser, where heat is rejected at constant pressure to a cooling medium such as water or air. As heat is removed, the steam condenses back into saturated liquid. The condensed water then returns to the pump, completing the cycle.

Thermal Efficiency of the Rankine Cycle

The thermal efficiency of the Rankine cycle is defined as the ratio of the net work output to the heat supplied in the boiler. It is expressed as:

$$\eta_{th} = \frac{W_{turbine} - W_{pump}}{Q_{boiler}}$$

A higher thermal efficiency indicates better utilization of the supplied heat. In practical power plants, techniques such as superheating, reheating, and regeneration are employed to improve the efficiency of the Rankine cycle.

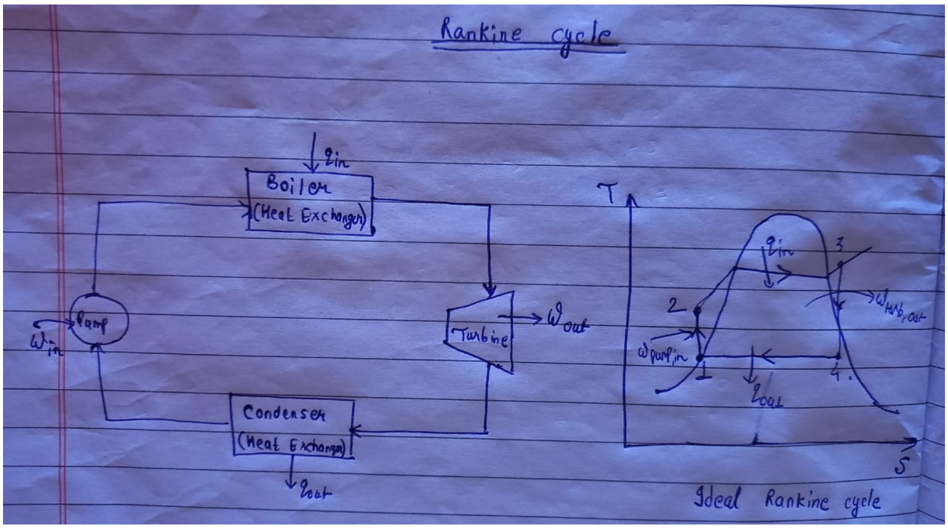

Figure 1: Schematic diagram and T–s diagram of the ideal Rankine cycle (hand-drawn)

Brayton Cycle

The Brayton cycle is the ideal thermodynamic cycle used in gas turbine power plants and jet engines. Unlike the Rankine cycle, the working fluid in the Brayton cycle remains in the gaseous state throughout the cycle. Air is commonly used as the working fluid, and the cycle operates on an open or closed basis depending on the application.

The Brayton cycle consists of four basic processes carried out in three main components: the compressor, combustion chamber, and turbine. For theoretical analysis, the ideal Brayton cycle assumes no internal irreversibilities and neglects pressure losses.

The four processes of the ideal Brayton cycle are:

- **Process 1–2: Isentropic compression in the compressor**
  In this, air enters the compressor at low pressure and temperature and is compressed isentropically to a higher pressure. As a result, both the pressure and temperature of the air increase, and work is required to drive the compressor.

- **Process 2–3: Constant-pressure heat addition in the combustion chamber**
  In this, the compressed air flows into the combustion chamber, where heat is added at nearly constant pressure. In actual gas turbines, this heat is supplied by fuel combustion, which significantly raises the temperature of the air.

- **Process 3–4: Isentropic expansion in the turbine**
  In this, the high-temperature, high-pressure gas expands isentropically through the turbine and produces work. Part of this work is used to operate the compressor, while the remaining work is available as useful output. During expansion, the pressure and temperature decrease.

- **Process 4–1: Constant-pressure heat rejection**
  In this, the exhaust gases reject heat at approximately constant pressure and return to the initial state. In open-cycle gas turbines, this heat is released directly to the atmosphere.

Thermal Efficiency of the Brayton Cycle

The thermal efficiency of the ideal Brayton cycle depends mainly on the pressure ratio of the compressor. It is given by:

$$\eta_{th} = 1 - \frac{1}{r_p^{(\gamma-1)/\gamma}}$$

where r_p is the pressure ratio and γ is the specific heat ratio.

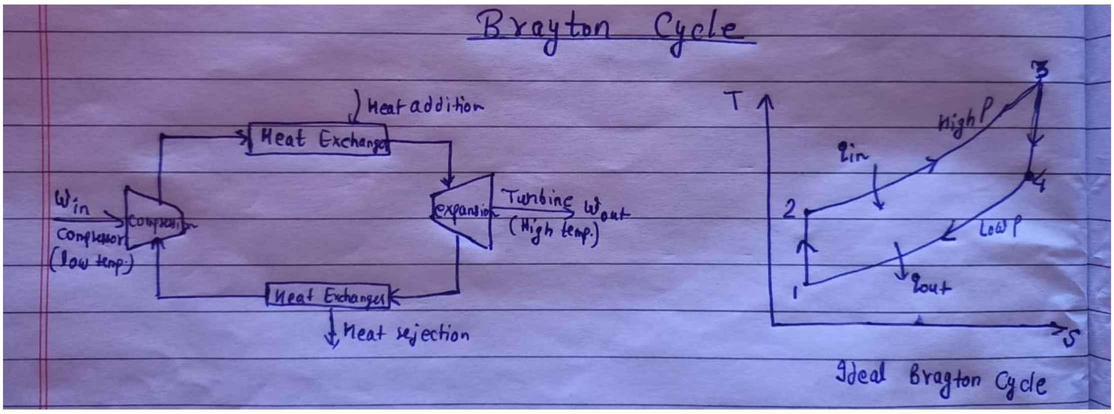

Figure 2: Schematic diagram and T–s diagram of the ideal Brayton cycle (hand-drawn)

Comparison of Rankine and Brayton Cycles

- Rankine cycle uses water as the working fluid.
- Brayton cycle uses air or gas as the working fluid.
- Rankine cycle involves phase change from liquid to vapor and back to liquid.
- Brayton cycle does not involve phase change.
- Rankine cycle consists of pump, boiler, turbine, and condenser.
- Brayton cycle consists of compressor, combustion chamber, and turbine.

In terms of applications, the Rankine cycle is commonly used in coal-fired, nuclear, and geothermal power plants for large-scale power generation. The Brayton cycle is widely used in gas turbine power plants, aircraft jet engines, and combined-cycle power plants.

Conclusion

This report discussed the basic theory of the Rankine and Brayton cycles used in power generation. Both cycles convert heat energy into useful work, but they operate in different ways and are used for different applications.

The Rankine cycle is mainly used in steam power plants and involves phase change of water. It is suitable for large and continuous power generation. The Brayton cycle operates with a gaseous working fluid and is commonly used in gas turbines and jet engines due to its compact design and quick operation.

Understanding these ideal cycles helps in analyzing real power plants and improving their efficiency. This study provides a basic foundation for further learning in thermodynamic power systems.

References

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