Consider A Simple Rankine Cycle With Water As Its Working Fluid. Water Exists The Condenser At 50 KPa

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The Rankine cycle is a fundamental thermodynamic cycle widely used in power generation systems, especially in thermal plants such as coal, nuclear, and concentrated solar power plants. When water serves as the working fluid, understanding its behavior and the cycle's operation is crucial for optimizing efficiency and ensuring safe operation. In this article, we explore a simple Rankine cycle with water as the working fluid, focusing on the condition where water exits the condenser at a pressure of 50 kPa. We will delve into the cycle's components, thermodynamic processes, calculations, and practical considerations to provide a comprehensive understanding.

Overview of the Rankine Cycle

The Rankine cycle operates on a sequence of four thermodynamic processes involving four key components: a boiler (or steam generator), a turbine, a condenser, and a pump. The cycle converts heat energy into mechanical work, which can then be transformed into electrical energy.

Basic Processes in the Rankine Cycle

1. **Heating and Vaporization in the Boiler:** Water is heated at constant pressure until it becomes high-pressure, high-temperature steam.

2. **Expansion in the Turbine:** The high-pressure steam expands through a turbine, producing work while its pressure and temperature decrease.

3. **Condensation in the Condenser:** The low-pressure steam is condensed back into liquid water at a constant pressure.

4. **Pressurization in the Pump:** The condensate is pressurized to the boiler pressure, completing the cycle.

The cycle repeats continuously, with the key goal being to maximize efficiency by optimizing each process.

Cycle Assumptions and Conditions

To analyze the cycle precisely, certain assumptions are typically made:

- The processes are steady-state and reversible (ideal cycle).
- The pump work is negligible compared to turbine work.
- Pressure drops in the boiler, condenser, and piping are ignored.
- Water behaves as a pure substance; properties are obtained from standard steam tables.

In our specific scenario, the condenser's exit pressure is given as 50 kPa, which influences the condenser temperature, the cycle's efficiency, and the thermodynamic properties of water at key points.

Thermodynamic State Points

The cycle involves four key state points:

- Point 1: Exit of the condenser (liquid water at 50 kPa)
- Point 2: Exit of the pump (liquid water at boiler pressure)
- Point 3: Exit of the boiler (superheated or saturated steam)
- Point 4: After expansion in the turbine (wet or superheated steam)

Let's analyze each point based on the given and typical properties.

State 1: Condensate Exit (Liquid Water at 50 kPa)

At 50 kPa, water exists as a saturated or slightly subcooled liquid. Using standard steam tables:

- Saturation temperature (Tsat): approximately 81.3°C
- Specific enthalpy of saturated liquid (hf): approximately 206.0 kJ/kg
- Specific entropy (sf): approximately 0.7333 kJ/kg·K

State 1 is typically considered as saturated liquid at 50 kPa, assuming the condenser operates at saturation conditions.

State 2: After Pump Compression

The pump increases the pressure of the liquid water from 50 kPa to the boiler pressure (often much higher, e.g., 10 MPa). Since the pump work is negligible, the enthalpy change across the pump (h2 - h1) can be approximated as:

- $W_{pump} \approx v \times \Delta P$

Where:

- v: specific volume of water at the inlet (approximately 0.001 m^3/kg)
- ΔP: pressure difference (from 50 kPa to boiler pressure, say 10 MPa)

Assuming a boiler pressure of 10 MPa:

- $W_{pump} \approx 0.001\ m^3/kg \times (10{,}000\ kPa - 50\ kPa) \approx 0.001 \times 9{,}950\ kPa \approx 9.95\ kJ/kg$

Thus:

- $h_2 \approx h_f + W_{pump} \approx 206.0 + 9.95 \approx 215.95\ kJ/kg$

State 2 is therefore saturated liquid (or slightly compressed) at 10 MPa.

State 3: After Heating in the Boiler

In an ideal cycle, the water is heated at constant pressure (10 MPa) until it reaches a desired temperature or the saturated vapor state.

- Saturation temperature at 10 MPa: approximately 179.9°C
- Enthalpy of saturated vapor (h_g): approximately 2778 kJ/kg
- Entropy (s_g): approximately 6.597 kJ/kg·K

Depending on the boiler's design, the steam may be superheated to a certain temperature, but for simplicity, we'll assume saturated vapor at this pressure.

State 4: After Expansion in the Turbine

The high-pressure steam expands through the turbine to the condenser pressure of 50 kPa, doing work in the process. The expansion is assumed isentropic (entropy remains constant):

- $s_4 = s_3 \approx 6.597\ kJ/kg \cdot K$

From the steam tables at 50 kPa:

- Saturation temperature: approximately 81.3°C

- Saturated vapor enthalpy (hg): approximately 2675 kJ/kg
- Saturated liquid enthalpy (hf): approximately 206.0 kJ/kg
- Saturation entropy (sg): approximately 6.59 kJ/kg·K

Since s4 ≈ sg, the steam at turbine exit is saturated vapor or slightly superheated, depending on the actual process. The enthalpy at point 4 can be interpolated:

- h4 ≈ hg at 50 kPa: approximately 2675 kJ/kg

Note: For precise analysis, the actual superheat or wetness fraction should be calculated, but for simplicity, we assume idealized saturated conditions.

Calculations of Cycle Performance

Understanding the cycle's efficiency involves calculating the work output, heat input, and thermal efficiency.

Work Done by the Turbine (W_t)

$$
W_{t} = h_{3} - h_{4}
$$

Assuming:

- $h_{3} \approx 2778\, \text{kJ/kg}$ (saturated vapor at 10 MPa)
- $h_{4} \approx 2675\, \text{kJ/kg}$ (expansion to 50 kPa)

Therefore:

$$
W_{t} \approx 2778 - 2675 = 103\, \text{kJ/kg}
$$

Work Done on the Pump (W_p)

From earlier:

$$
W_{p} \approx 9.95\, \text{kJ/kg}
$$

Net Work Output (W_{net})

$$
W_{net} = W_{t} - W_{p} \approx 103 - 9.95 = 93.05\, \text{kJ/kg}
$$

Heat Input (Q_{in})

The heat added in the boiler is:

$$
Q_{in} = h_{3} - h_{2}
$$

Using:

- $h_{3} \approx 2778\, \text{kJ/kg}$
- $h_{2} \approx 215.95\, \text{kJ/kg}$

Thus:

$$
Q_{in} \approx 2778 - 215.95 = 2562.05\, \text{kJ/kg}
$$

Thermal Efficiency (η)

$$
\eta = \frac{W_{net}}{Q_{in}} \approx \frac{93.05}{2562.05} \approx 3.63\%
$$

This low efficiency indicates the cycle's limitations under idealized assumptions with such a low condenser pressure. Real systems incorporate regenerative heating, reheating, and other enhancements to improve efficiency.

Impact of Condenser Pressure on Cycle Performance

The condenser pressure significantly influences the Rankine cycle's efficiency. Lower condenser

Frequently Asked Questions

What is the basic working principle of a simple Rankine cycle using water as the working fluid?

The simple Rankine cycle operates by converting heat energy into mechanical work through four main processes: water is pumped to high pressure, heated in a boiler to produce high-pressure vapor, expanded in a turbine to generate work, and then condensed back to liquid in a condenser, completing the cycle.

What is the significance of the condenser pressure being 50 kPa in a Rankine cycle?

The condenser pressure of 50 kPa determines the condensing temperature, which affects the cycle's efficiency. Lower condenser pressure generally improves efficiency by increasing the temperature difference between the boiler and condenser, but it also requires more expansive condenser equipment.

How does operating the condenser at 50 kPa influence the cycle’s thermal efficiency?

Operating the condenser at 50 kPa lowers the condensing temperature, which increases the temperature difference between the heat source and sink, thus potentially increasing the cycle's thermal efficiency.

What are the typical saturation temperature and quality of water at 50 kPa in the condenser?

At 50 kPa, the saturation temperature of water is approximately 45.8°C. The exiting condensate is usually a saturated or subcooled liquid, with a quality close to zero if fully condensed.

What are the typical challenges or limitations of operating a simple Rankine cycle with water at a condenser pressure of 50 kPa?

Challenges include dealing with low condensing temperatures that can cause material and operational issues, increased size and cost of condensers, and potential for moisture carryover and erosion in turbines due to wet steam conditions.

How does the condenser pressure of 50 kPa affect the overall cycle efficiency and power output?

A condenser pressure of 50 kPa tends to improve cycle efficiency by increasing the temperature difference in the cycle, leading to higher net work output compared to higher condenser pressures, but it may also reduce the maximum achievable power if other parameters are fixed.

What is the impact of the condenser pressure on the turbine inlet conditions in a simple Rankine cycle?

The condenser pressure influences the condenser exit condition, which in turn affects the boiler inlet pressure and temperature. Lower condenser pressures lead to higher boiling temperatures, potentially increasing the work output per cycle.

How would increasing the condenser pressure above 50 kPa affect the cycle’s performance?

Increasing the condenser pressure raises the condensing temperature, reducing the temperature difference in the cycle, which decreases thermal efficiency and net work output. It can also lead to higher back pressure on the turbine, lowering its efficiency.

What are some practical considerations when designing a condenser for a Rankine cycle operating at 50 kPa?

Design considerations include ensuring adequate heat transfer surface area, controlling subcooling to prevent vaporization, managing moisture content, and selecting materials resistant to corrosion and erosion caused by wet steam conditions at low pressure.

Additional Resources

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Introduction

The Rankine cycle remains a fundamental thermodynamic cycle underpinning many of today's thermal power plants. Its simplicity and efficiency make it a preferred choice for converting heat into useful work, especially when water is employed as the working fluid. In this article, we examine a basic Rankine cycle operating under specific conditions—particularly focusing on the scenario where the condenser pressure is set at 50 kPa. Through this exploration, we will unpack the cycle's components, analyze its thermodynamic behavior, and evaluate its performance metrics, providing a comprehensive understanding of how such a system functions in real-world applications.

The Fundamentals of the Rankine Cycle

Before diving into the specifics of our scenario, it's essential to grasp the core principles of the Rankine cycle. This cycle is a closed-loop process that involves four primary processes:

1. Water Pumping (Pressurization): Liquid water is pumped from the condenser pressure to the boiler pressure.
2. Boiler Heating (Vaporization): The high-pressure water is heated at constant pressure, converting into high-temperature, high-pressure steam.
3. Expansion (Work Extraction): The steam expands through a turbine, generating work while decreasing in temperature and pressure.
4. Condensation: The exhaust steam is condensed back into liquid water at low pressure, completing the cycle.

This sequence repeats, enabling the conversion of thermal energy into mechanical work, which can then be transformed into electrical energy.

Setting the Stage: Operating Conditions and Assumptions

For our specific analysis, we consider a simple Rankine cycle with the following parameters:

- Working Fluid: Water
- Condenser Pressure: 50 kPa (0.05 MPa)
- Boiler Pressure: Assumed to be 10 MPa (a typical high-pressure scenario for efficiency)
- Heat Source Temperature: Corresponds to the boiler pressure—approximately 550°C, considering typical superheated conditions
- Negligible Pump Work: Due to the relatively small specific volume of liquid water
- Ideal Cycle Assumption: No irreversibilities or pressure drops within components

These assumptions streamline the analysis while still capturing the cycle's essential behavior.

Thermodynamic States and Properties

Understanding the cycle requires analyzing the thermodynamic states at key points:

- State 1: Exit of the condenser, saturated liquid water at 50 kPa
- State 2: After the pump, high-pressure liquid water entering the boiler
- State 3: Superheated steam after the boiler
- State 4: Exhaust steam after expansion through the turbine, before condensation

Let's delve into each state:

State 1: Condensed Liquid Water at 50 kPa

At 50 kPa, the saturation temperature of water is approximately 81.3°C. The water is in a saturated liquid state, meaning it exists entirely as liquid with negligible vapor content. Its specific enthalpy and entropy can be obtained from standard steam tables:

- Enthalpy (h_1): ~340.5 kJ/kg
- Entropy (s_1): ~1.307 kJ/kg·K

State 2: Pumped Liquid Water at Boiler Pressure

The pump increases the pressure from 50 kPa to 10 MPa. Because water's specific volume is small, pump work is minimal:

- Work input (W_pump): ≈ $v(P_2 - P_1)$

Where:

- $v \approx 0.001$ m³/kg (liquid water's specific volume)
- $P_2 = 10$ MPa, $P_1 = 0.05$ MPa

Calculations:

W_pump ≈ 0.001 m³/kg (10,000 kPa - 50 kPa) ≈ 9.95 kJ/kg

Enthalpy at this point:

$h_2 \approx h_1$ + W_pump ≈ 340.5 + 9.95 ≈ 350.45 kJ/kg

State 3: Superheated Steam at Boiler Exit

Suppose the boiler heats water to a superheated state at 10 MPa and 550°C. From steam tables:

- Enthalpy (h_3): ≈ 3,050 kJ/kg
- Entropy (s_3): ≈ 6.59 kJ/kg·K

State 4: After Expansion in the Turbine

The high-pressure steam expands adiabatically in the turbine to the condenser pressure (50 kPa). Assuming ideal (isentropic) expansion:

$s_4 = s_3 \approx 6.59$ kJ/kg·K

From the steam tables, at 50 kPa with entropy s_4:

- Enthalpy (h_4): approximately 2,260 kJ/kg

This indicates a significant drop in energy, which translates into work output.

Calculating Cycle Performance Metrics

With the key states defined, we can now evaluate the cycle's efficiency and work outputs.

Work Done by the Turbine (W_turbine)

$W\_turbine = h_3 - h_4 \approx 3{,}050 - 2{,}260 = 790$ kJ/kg

Work Input to the Pump (W_pump)

As previously calculated:

$W\_pump \approx 10$ kJ/kg

Net Work Output (W_net)

$W\_net = W\_turbine - W\_pump \approx 790 - 10 = 780$ kJ/kg

Heat Added in the Boiler (Q_in)

$Q\_in = h_3 - h_2 \approx 3{,}050 - 350.45 \approx 2{,}699.55$ kJ/kg

Heat Rejected in the Condenser (Q_out)

$Q\_out = h_4 - h_1 \approx 2{,}260 - 340.5 \approx 1{,}919.5$ kJ/kg

Thermal Efficiency (η)

Efficiency is the ratio of net work output to heat input:

$\eta = W\_net / Q\_in \approx 780 / 2{,}699.55 \approx 28.9\%$

This efficiency aligns with typical modern Rankine cycle efficiencies, especially considering the simplified assumptions.

Impact of Condenser Pressure on Cycle Performance

The condenser pressure plays a pivotal role in the cycle's efficiency. Operating at a low condenser pressure (like 50 kPa) allows for greater expansion of the steam, resulting in higher work output per cycle. Let's analyze this influence:

Lowering condenser pressure:

- Increases the pressure differential across the turbine, allowing more energy to be extracted.
- Decreases the condenser temperature, improving the temperature gradient and potentially increasing efficiency.
- Potential challenges: Pumping water to higher pressures requires more work; also, low-pressure condensers may need larger cooling systems.

Operating at 50 kPa:

- The saturation temperature is about 81.3°C, which is relatively low, aiding in higher efficiency.
- The cycle benefits from the larger enthalpy difference between the turbine inlet and

exhaust states.

However, in practical scenarios, operating at such low condenser pressures demands sophisticated cooling systems, especially in climates with high ambient temperatures.

Practical Considerations and Limitations

While the idealized analysis provides valuable insights, real-world Rankine cycles are subject to various practical constraints:

- Irreversibilities: Mechanical losses, pressure drops, and heat transfer inefficiencies reduce actual performance.
- Material Limitations: High-pressure and high-temperature components require advanced materials to withstand operational stresses.
- Economic Factors: Increasing the condenser or boiler pressures can involve higher capital costs, influencing overall plant economics.
- Environmental Impact: Cooling systems at low condenser pressures may require significant water resources, raising sustainability concerns.

Despite these, optimizing condenser pressure remains a key strategy in enhancing power plant efficiency.

Advances and Innovations in Cycle Optimization

To improve upon the basic Rankine cycle, engineers explore several modifications:

- Superheating: Raising the steam temperature beyond saturation to increase enthalpy difference.
- Reheat Cycles: Expanding the steam in multiple turbines separated by reheating stages to boost efficiency.
- Regenerative Cycles: Incorporating feedwater heaters to preheat water before entering the boiler, reducing fuel consumption.
- Binary Cycles and Organic Rankine Cycles: Utilizing organic fluids with lower boiling points for waste heat recovery or low-temperature applications.

Each of these approaches aims to maximize energy extraction, reduce emissions, and improve overall system economics.

Conclusion

Analyzing a simple Rankine cycle with water as the working fluid and a condenser pressure of 50 kPa reveals the intricate balance between thermodynamic principles and engineering practicality. Operating at low condenser pressures enhances efficiency by enabling greater expansion of steam, but it also introduces operational challenges. This cycle's performance hinges on meticulous design choices—such as boiler pressure, superheat temperature, and condenser conditions—all of which influence the cycle's ability to convert heat into power effectively.

As energy demands grow and sustainability becomes paramount, understanding and optimizing such fundamental cycles remain crucial. Whether through incremental improvements or innovative technological advancements, the basic principles outlined here continue to underpin the evolution of thermal power generation worldwide.

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