Problem 5Steam Enters A Turbine, At A Rate Of 10 Kg/s At 4000 KPa And 300 C. Then The Steam Is Exhausted

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Understanding the thermodynamics of turbines is essential for the design, analysis, and optimization of power plants and various industrial processes. In this problem, we analyze the behavior of steam as it enters a turbine at specified conditions and then exits after performing work. The goal is to determine key parameters such as the work output, efficiency, and entropy changes involved in this process.

Introduction to Steam Turbine Processes

Steam turbines are devices that convert the thermal energy of steam into mechanical work. They are widely used in electricity generation, propulsion, and industrial applications. The working principle involves high-pressure steam expanding through the turbine blades, causing the rotor to spin and generate power.

Key concepts involved include:

- Thermodynamic cycle analysis
- Energy transfer and work output
- Mass and energy balances
- Entropy and irreversibilities

Understanding these principles allows engineers to optimize turbine performance, improve efficiency, and ensure safe operation.

Given Data and Assumptions

The problem provides the following data:

1. Mass flow rate of steam, $\dot{m}$ = 10 kg/s
2. Inlet pressure, P_1 = 4000 kPa (or 4 MPa)
3. Inlet temperature, T_1 = 300°C
4. The steam expands through the turbine and is exhausted, with unknown conditions at the outlet.

Assumptions:

- Steady-state operation
- No heat transfer to surroundings (adiabatic process)
- No shaft work interactions other than the turbine work
- Isentropic expansion for ideal analysis (unless specified otherwise)
- Using saturated and superheated steam tables for property data

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Thermodynamic Analysis of the Turbine

The key goal is to determine the work output per unit mass, the power generated, and the entropy change associated with the process.

1. State Properties at the Inlet

Using the given inlet conditions:

- Pressure $P_1 = 4000\, \text{kPa}$
- Temperature $T_1 = 300^\circ C$

Consult steam tables or Mollier charts:

Property	Value
Specific volume, v_1	approximately 0.257 m^3/kg (superheated steam at 300°C and 4 MPa)
Specific enthalpy, h_1	approximately 3067 kJ/kg
Specific entropy, s_1	approximately 6.73 kJ/kg·K

(Values are approximate; actual data should be obtained from detailed steam tables.)

2. State Properties at the Outlet

Since the process is expansion through a turbine, the outlet conditions depend on the expansion process—whether it is isentropic or involves irreversibilities.

Assuming ideal isentropic expansion:

- The entropy at the outlet s_2 equals s_1: $s_2 = s_1 = 6.73\, \text{kJ/kg·K}$

- At the same entropy, locate the state on the saturated or superheated steam tables at the same entropy and find the corresponding pressure and enthalpy.

Possible outlet conditions:

- Usually, the steam is expanded to a lower pressure, say P_2. For illustrative purposes, assume $P_2 = 100\, \text{kPa}$.

- From the steam tables at $s = 6.73\, \text{kJ/kg·K}$ and $P = 100\, \text{kPa}$:

- Saturation temperature $T_{sat} \approx 99.6^\circ C$

- The properties indicate superheated steam at these conditions with $h_2 \approx 2670\, \text{kJ/kg}$

Note: Actual outlet conditions should be specified or determined based on system design.

3. Work Output Calculation

The work done by the turbine per unit mass:

$$
W_{t} = h_1 - h_2
$$

Total power output:

$$
\dot{W} = \dot{m} \times W_{t}
$$

Using approximate enthalpy values:

$$
W_{t} = 3067\, \text{kJ/kg} - 2670\, \text{kJ/kg} = 397\, \text{kJ/kg}
$$

$$
\dot{W} = 10\, \text{kg/s} \times 397\, \text{kJ/kg} = 3970\, \text{kW}
$$

\]

Thus, the turbine produces approximately 3.97 MW of power under ideal conditions.

Assessing Real-World Efficiency and Irreversibilities

In practice, turbines are not perfectly isentropic; there are irreversibilities due to friction, turbulence, and other factors.

1. Isentropic Efficiency of the Turbine

Defined as:

$$
\eta_{t} = \frac{\text{Actual work output}}{\text{Isentropic work output}}
$$

- Actual work can be less than ideal due to entropy generation.

- To estimate actual work, determine actual enthalpy at the outlet considering efficiency:

$$
h_{2, actual} = h_1 - \eta_{t} \times (h_1 - h_{2,s})
$$

Where $h_{2,s}$ is the enthalpy at the ideal (isentropic) expansion point.

Typical turbine efficiencies range from 85% to 95%.

2. Entropy Generation and Irreversibility

The change in entropy:

$$
\Delta s = s_2 - s_1
$$

- For ideal isentropic expansion, $\Delta s = 0$.

- In real turbines, $\Delta s > 0$, indicating entropy generation and irreversibility.

Additional Considerations for Steam Turbine Analysis

1. Heat Losses and External Effects

- Actual turbines may experience heat transfer losses, affecting overall efficiency.

2. Condensation and Wetness

- Expansion to very low pressures can cause partial condensation, leading to wet steam and blade erosion.

3. Reheat and Regenerative Cycles

- Many power plants employ reheating and feedwater regeneration to improve efficiency.

Conclusion and Summary

In this analysis, we have examined the thermodynamic behavior of steam entering a turbine at specified conditions and expanded through an idealized process. The key takeaways include:

- The inlet conditions of 4000 kPa and 300°C correspond to superheated steam with high enthalpy.

- Assuming ideal isentropic expansion, the turbine can generate approximately 3.97 MW of power with a mass flow rate of 10 kg/s.

- Real turbines operate with efficiencies less than 100%, and entropy generation indicates irreversibility.

- Proper understanding of steam properties via tables and charts is essential for accurate design and performance evaluation.

- Additional factors such as reheat, regenerative cycles, and losses influence actual performance and should be considered for comprehensive system analysis.

References and Resources for Further Study

- Steam Tables and Mollier Charts: Essential for accurate thermodynamic property data.
- Thermodynamics Textbooks: "Fundamentals of Engineering Thermodynamics" by Moran and Shapiro provides detailed explanations.
- Power Plant Engineering: For practical applications and cycle optimization.
- Simulation Software: Tools like EES (Engineering Equation Solver) or REFPROP facilitate detailed

analysis.

If you are working on a related project or need to perform detailed design calculations, always ensure to use the latest property data and consider real-world efficiency factors to obtain accurate results.

Frequently Asked Questions

What is the initial state of the steam entering the turbine in Problem 5?

The steam enters the turbine at a rate of 10 kg/s, with a pressure of 4000 kPa and a temperature of 300°C.

How do you determine the enthalpy of the steam at the turbine inlet in this problem?

The enthalpy can be found using steam tables or Mollier charts based on the given pressure (4000 kPa) and temperature (300°C).

What is the significance of knowing the mass flow rate of 10 kg/s in analyzing the turbine's performance?

The mass flow rate helps calculate power output, work done by the turbine, and energy transfer rates, providing insight into efficiency and capacity.

What are the typical assumptions made when analyzing a steam turbine in thermodynamics problems like this?

Common assumptions include steady-flow operation, adiabatic process (no heat loss), reversible expansion, and neglecting minor losses.

How does the exhaust condition of the steam affect the overall energy balance in the turbine?

The exhaust conditions determine the exit enthalpy and entropy, affecting the work output and efficiency of the turbine.

What additional data is needed to fully analyze the turbine's work output and efficiency in this problem?

Detailed exit conditions such as exhaust pressure or temperature are needed, along with enthalpy values at the inlet and outlet.

Why is it important to consider the entropy change during the steam expansion in the turbine?

Entropy change indicates the irreversibility of the process and helps evaluate the efficiency and thermodynamic quality of the expansion.

Additional Resources

Steam Enters a Turbine, at a Rate of 10 kg/s at 4000 kPa and 300°C: A Comprehensive Thermodynamic Analysis

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Introduction

In the realm of power generation and thermodynamic systems, turbines play a pivotal role in converting thermal energy into mechanical work, which can then be transformed into electrical energy. The performance and efficiency of turbines are critically dependent on the properties of the steam entering and exiting the turbine, as well as the operational parameters such as mass flow rate, pressure, and temperature. This detailed review delves into the thermodynamic principles governing a typical steam turbine process, focusing on the problem where steam enters a turbine at a rate of 10 kg/s, with inlet conditions of 4000 kPa and 300°C, and then exhausts.

Overview of the Turbine Process

The problem involves several key elements:

- Mass flow rate: 10 kg/s
- Inlet conditions:
- Pressure, $P_1 = 4000 \text{ kPa}$ (or 4 MPa)
- Temperature, $T_1 = 300^\circ C$
- Exhaust conditions: To be determined based on the thermodynamic analysis
- Objective: To analyze the energy transfer, efficiency, enthalpy changes, and entropy considerations during the process

Understanding these elements requires a comprehensive grasp of the properties of steam, the thermodynamic cycle involved, and the relevant calculations.

Thermodynamic Properties of the Inlet Steam

1. State 1: Inlet Conditions

At the inlet, the steam is at a high pressure and temperature, typical of superheated steam in power plant turbines. To accurately analyze the process, precise thermodynamic properties are necessary, which can be obtained from steam tables or Mollier diagrams.

- Pressure: 4000 kPa (4 MPa)
- Temperature: 300°C

Using superheated steam tables or software (such as NIST REFPROP or IAPWS standards), the properties at this state are:

Property	Value
Enthalpy, h_1	Approximately 2778 kJ/kg
Entropy, s_1	Approximately 6.75 kJ/kg·K
Specific volume, v_1	Approximately 0.257 m^3/kg

(Values are approximate; actual values depend on the source data)

2. State 2: Exhaust Conditions

The steam expands through the turbine, doing work, and its pressure drops. The exhaust state is characterized by:

- Pressure, P_2: Typically the condenser pressure (e.g., 10 kPa to 100 kPa)
- Temperature, T_2: To be determined based on the expansion process

The key thermodynamic questions include:

- What is the exit enthalpy h_2?
- What is the work output?
- How much entropy generation occurs?

Thermodynamic Analysis of the Turbine Process

1. Assumptions

For simplicity and clarity, several assumptions are made:

- The process is steady-state and steady-flow.
- The turbine operates adiabatically, with negligible heat transfer.
- There are no irreversibilities (ideal process) unless otherwise specified.
- Kinetic and potential energy changes are negligible.
- The inlet conditions are known precisely.

2. Energy Balance

The fundamental energy equation for the turbine (steady-flow energy equation):

$$
\dot{m}(h_1 + \frac{v_1^2}{2} + gz_1) = \dot{m}(h_2 + \frac{v_2^2}{2} + gz_2) + W_{t}

\]

Neglecting kinetic and potential energy changes:

$$
W_{t} = \dot{m}(h_1 - h_2)
$$

Where:

- W_t = Power output of the turbine (kW)
- $\dot{m}$ = mass flow rate (kg/s)
- h_1, h_2 = specific enthalpy at inlet and outlet

Given the mass flow rate:

$$
W_{t} = 10 \times (h_1 - h_2) \quad \text{(kW)}
$$

The primary task is to determine h_2, which depends on the expansion process.

Ideal vs. Real Expansion Processes

1. Isentropic Expansion (Ideal Case)

In an ideal, reversible adiabatic expansion:

$$
s_1 = s_2
$$

Using the inlet entropy s_1, the exit enthalpy h_2 can be obtained from the steam tables at the exhaust pressure P_2, ensuring the entropy remains constant.

Example:

- If the condenser pressure is 10 kPa (or 0.1 MPa), then:

- Find the saturated vapor enthalpy at 10 kPa, $h_{g@10kPa}$, typically around 2676 kJ/kg
- Find the entropy at this pressure, $s_{g@10kPa}$, around 8.15 kJ/kg·K

- Since the process is isentropic:

$$
s_2 = s_1 = 6.75 \text{ kJ/kg·K}
$$

- At 10 kPa, the saturated vapor entropy is higher (8.15), so the steam is superheated or wet during expansion, and the actual h_2 is somewhere between the saturated liquid and vapor enthalpies.

Using superheated steam tables, interpolate to find h_2 at $s_2 = 6.75$ and $P_2 = 10 \text{ kPa}$. This yields an approximate h_2 around 2400–2500 kJ/kg.

2. Real Expansion: Irreversible Process

In practical turbines, irreversibilities cause entropy to increase:

$$
s_2 > s_1
$$

This results in a decreased work output compared to the ideal scenario, and the entropy generation indicates the irreversibility magnitude.

Calculating Work Output and Efficiency

1. Work Output

For the ideal (isentropic) case:

$$
W_{t,ideal} = \dot{m} (h_1 - h_{2s})
$$

where h_{2s} is the enthalpy at the exhaust state assuming isentropic expansion.

Suppose:

- $h_1 \approx 2778 \text{ kJ/kg}$
- $h_{2s} \approx 2400 \text{ kJ/kg}$ (from the tables)

Then:

$$
W_{t,ideal} = 10 \times (2778 - 2400) = 10 \times 378 = 3780 \text{ kW}
$$

This is the maximum theoretical power output.

2. Actual Power Output

In real turbines, due to irreversibility, the actual enthalpy at the exit, h_2, will be higher, reducing the work:

$$
W_{t,actual} = 10 \times (h_1 - h_2)
$$

If, for example, h_2 is 2450 kJ/kg:

$$
W_{t,actual} = 10 \times (2778 - 2450) = 10 \times 328 = 3280 \text{ kW}
$$

The efficiency of the turbine is then:

$$
\eta_{t} = \frac{W_{t,actual}}{W_{t,ideal}} \times 100\%
$$

$$
\eta_{t} \approx \frac{3280}{3780} \times 100\% \approx 86.7\%
$$

which is typical for well-designed turbines.

Entropy Generation and Irreversibility

The increase in entropy during expansion reflects irreversibilities:

$$
\Delta s = s_2 - s_1 > 0
$$

For the ideal process:

$$
s_2 = s_1 = 6.75 \text{ kJ/kg·K}
$$

In real turbines, s_2 might be around 7.0–7.2 kJ/kg·K, indicating entropy production.

This entropy generation corresponds to lost work potential and is a key factor in assessing turbine performance.

Exergy and Losses

The concept of exergy helps quantify the maximum useful work obtainable:

$$
\text{Exergy destruction} = T_0 \times \Delta s_{irreversible}
$$

where:

- T_0 = ambient temperature (assumed 25°C or 298 K)
- $\Delta s_{irreversible}$ = entropy generated during expansion

Higher entropy generation signifies greater exergy destruction, reducing overall system efficiency.

Practical Considerations in Turbine Design and Operation

1. Material Constraints

- High inlet temperature and pressure demand robust materials capable of withstanding thermal stresses.
- Blade design must accommodate high velocities and pressure

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