One Cubic Meter Of An Ideal Gas At 600 K And 1000 Malek KPa Expands To Five Times Its Initial Volume

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Understanding the behavior of gases under different conditions is fundamental in thermodynamics and engineering applications. When an ideal gas undergoes expansion, its pressure, volume, and temperature change according to well-established laws. In this article, we delve into a specific scenario where a gas initially occupies a volume of one cubic meter at a temperature of 600 K and a pressure of 1000 Malek KPa, and then expands to five times its original volume. We will analyze the process using principles such as the ideal gas law, thermodynamic equations, and practical implications.

Initial Conditions of the Gas

Before exploring the expansion process, it's essential to understand the initial state of the gas.

Initial Volume (V_1)

- $V_1 = 1\ m^3$

Initial Temperature (T_1)

- $T_1 = 600$ K

Initial Pressure (P_1)

- $P_1 = 1000$ Malek KPa

Understanding the Units: Malek KPa

- Malek KPa is a unit of pressure. For standard calculations, it's often necessary to convert to Pascals (Pa):

1 Malek KPa = 1,000,000 Pa

Therefore,

P_1 = 1000 Malek KPa = 1,000,000,000 Pa (or 1 GPa)

Note: The high pressure indicates a dense or high-pressure environment, which is typical in specialized industrial processes.

Applying the Ideal Gas Law

The behavior of ideal gases is governed by the ideal gas law:

$$ PV = nRT $$

Where:
- P = pressure
- V = volume
- n = number of moles
- R = universal gas constant (~8.314 J/(mol·K))
- T = temperature in Kelvin

Since the process involves a single sample and the gas is ideal, we assume n remains constant during the expansion.

Calculating the Number of Moles (n) Initially

Rearranged as:

$$ n = \frac{PV}{RT} $$

Plugging in the initial conditions:

$$ n = \frac{(1 \times 10^9\, \text{Pa}) \times 1\, \text{m}^3}{8.314\, \text{J/(mol·K)} \times 600\, \text{K}} $$

$$ n \approx \frac{1 \times 10^9}{8.314 \times 600} $$

$$ n \approx \frac{1 \times 10^9}{4988.4} $$

$$ n \approx 200,448\, \text{mol} $$

This is the amount of gas initially present.

The Expansion to Five Times the Initial Volume

The problem states that the gas expands to five times its original volume.

Final Volume (V_2)

- $V_2 = 5 \times V_1 = 5\ m^3$

Since the amount of gas (n) remains constant, the change in pressure and temperature depends on the nature of the process.

Analyzing the Expansion Process

The key question is: what is the nature of the process? Is it isothermal, adiabatic, or polytropic? The answer determines how pressure and temperature change during the expansion.

Assumption 1: Isothermal Expansion

If the expansion occurs at constant temperature ($T_2 = T_1$), then:

$$ PV = \text{constant} $$

So,

$$ P_2 = \frac{nRT}{V_2} $$

Given initial state:

$$ P_1V_1 = P_2V_2 $$

$$ P_2 = P_1 \times \frac{V_1}{V_2} = 1 \times 10^9\, \text{Pa} \times \frac{1}{5} = 2 \times 10^8\, \text{Pa} $$

Thus, the pressure drops to 200 MPa during expansion.

Temperature remains at 600 K in this idealized case.

Assumption 2: Adiabatic Expansion

If the process is adiabatic (no heat exchange), then:

$$ PV^\gamma = \text{constant} $$

Where:

- $\gamma = c_p/c_v$, the heat capacity ratio. For an ideal gas, γ depends on the specific gas. Typical values:
- Diatomic gases (like nitrogen, oxygen): $\gamma \approx 1.4$

- Monatomic gases (like noble gases): $\gamma \approx 1.67$

Assuming a diatomic ideal gas:

$$ P_2 = P_1 \times \left(\frac{V_1}{V_2}\right)^\gamma $$

$$ P_2 = 1 \times 10^9\, \text{Pa} \times \left(\frac{1}{5}\right)^{1.4} $$

Calculating:

$$ \left(\frac{1}{5}\right)^{1.4} \approx e^{1.4 \times \ln(1/5)} $$

$$ \ln(1/5) \approx -1.6094 $$

$$ 1.4 \times -1.6094 \approx -2.253 $$

$$ e^{-2.253} \approx 0.105 $$

Therefore,

$$ P_2 \approx 1 \times 10^9\, \text{Pa} \times 0.105 \approx 1.05 \times 10^8\, \text{Pa} $$

The pressure decreases significantly but not as much as in the isothermal case.

The temperature after expansion (T_2) can be found using the adiabatic relation:

$$ T_2 = T_1 \times \left(\frac{V_1}{V_2}\right)^{\gamma - 1} $$

$$ T_2 = 600\, \text{K} \times \left(\frac{1}{5}\right)^{0.4} $$

Calculate:

$$ \left(\frac{1}{5}\right)^{0.4} \approx e^{0.4 \times -1.6094} \approx e^{-0.6438} \approx 0.525 $$

So,

$$ T_2 \approx 600 \times 0.525 \approx 315\, \text{K} $$

In adiabatic expansion, the temperature drops from 600 K to approximately 315 K.

Implications of the Expansion

The nature of the process significantly influences the thermodynamic properties during expansion.

Energy Considerations

- Work Done by the Gas (W):

For expansion from V_1 to V_2:

$$ W = \int_{V_1}^{V_2} P\, dV $$

- In isothermal process:

$$ W = nRT \ln \frac{V_2}{V_1} $$

$$ W = 200,448 \times 8.314 \times 600 \times \ln 5 $$

$$ W \approx 200,448 \times 8.314 \times 600 \times 1.6094 $$

$$ W \approx 200,448 \times 8.314 \times 600 \times 1.6094 $$

Calculate step-by-step:

- $ 8.314 \times 600 \approx 4988.4 $

- $ 200,448 \times 4988.4 \approx 1.000 \times 10^{9} $ (roughly equal to initial PV)

- Multiply by 1.6094:

$$ W \approx 1 \times 10^{9} \times 1.6094 \approx 1.609 \times 10^{9} \text{J} $$

- In adiabatic process, the work done is less because the temperature drops, and the process involves both work and heat transfer.

Final State Properties

- Final Volume: 5 m^3
- Final Pressure: Varies depending on the process (approximately 200 MPa in isothermal, 105 MPa in adiabatic)
- Final Temperature: 600 K (isothermal) or ~315 K (adiabatic)

Practical Applications and Real-World Relevance

Understanding such expansion processes has numerous applications across industries.

Industrial Gas Storage and Transportation

- High-pressure gases are stored in cylinders or tanks.
- Expansion processes are critical in designing safety protocols and calculating energy exchanges.

Power Generation and Thermodynamic Cycles

- Expansion of gases is fundamental in turbines and engines.
- The efficiency of turbines depends on adiabatic expansion and temperature drops.

Refrigeration and Air Conditioning

- Expansion valves operate similarly to controlled gas expansion, cooling the system.

Conclusion

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Frequently Asked Questions

What is the initial state of the ideal gas in terms of temperature, volume, and pressure?

The initial state has a temperature of 600 K, a volume of 1 cubic meter, and a pressure of 1000 kPa.

What is the final volume of the gas after expansion?

The gas expands to five times its initial volume, so the final volume is 5 cubic meters.

How does the pressure of the gas change during the expansion if the process is isothermal?

If the expansion is isothermal (constant temperature), the pressure decreases proportionally to volume, so the final pressure would be 1000 kPa divided by 5, resulting in 200 kPa.

What is the work done by the gas during this expansion?

The work done by the gas during an expansion from volume V_1 to V_2 at constant temperature is $W = nRT \ln(V_2/V_1)$. To calculate this, we need the number of moles n, which can be found using $PV = nRT$.

How can the change in internal energy be determined for this expansion?

For an ideal gas, the internal energy depends only on temperature. Since temperature remains constant in an isothermal process, the change in internal energy is zero.

What assumptions are made about the gas during this expansion process?

The gas is assumed to be ideal, the process is quasi-static (reversible), and temperature remains constant if the process is isothermal. If not specified, other processes like adiabatic or polytropic could be considered, but with the given data, ideal conditions are assumed.

Additional Resources

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Introduction

In the realm of thermodynamics and gas behavior, understanding how gases respond to various conditions is crucial for both theoretical insights and practical applications. Among the fundamental concepts is the behavior of an ideal gas when subjected to changes in volume, temperature, and pressure. This article delves into a specific scenario involving an ideal gas initially occupying a volume of one cubic meter at a temperature of 600 K and a pressure of 1000 kPa, which subsequently expands to five times its original volume. We will explore the thermodynamic principles governing such a process, analyze the implications of the expansion, and discuss the various parameters that describe the state of the gas throughout this transformation.

Initial Conditions and Basic Assumptions

Initial State of the Gas

- Volume (V_1): 1 m^3
- Temperature (T_1): 600 K
- Pressure (P_1): 1000 kPa

Assumptions

- The gas behaves ideally, meaning it follows the ideal gas law:
$$PV = nRT$$
where P is pressure, V is volume, n is the number of moles, R is the universal gas constant, and T is temperature.

- The process is either quasi-static (reversible) or involves specific thermodynamic pathways, though the fundamental relationships hold in either case.

- The number of moles n remains constant during the expansion (no mass transfer).

Thermodynamic Foundations

The Ideal Gas Law and Its Significance

The ideal gas law serves as the cornerstone for analyzing such processes. It relates the macroscopic properties of the gas to the microscopic behavior of molecules. Applying it to the initial state:

$$P_1 V_1 = n R T_1$$

Given the initial parameters, one can determine the amount of gas (in moles):

$$n = \frac{P_1 V_1}{R T_1}$$

Using the universal gas constant $R \approx 8.314\, \mathrm{J/(mol \cdot K)}$:

$$n = \frac{1000 \times 10^3 \, \mathrm{Pa} \times 1\, \mathrm{m^3}}{8.314\, \mathrm{J/(mol \cdot K)} \times 600\, \mathrm{K}}$$

$$n \approx \frac{1 \times 10^6}{4,988.4} \approx 200.4\, \mathrm{mol}$$

This calculation provides the basis for analyzing the subsequent state.

The Expansion Process: From Initial to Final State

Final Volume (V_2): 5 m^3 (five times the initial volume)

Since the process involves an expansion to five times the initial volume, the key questions are:

- How do pressure and temperature change during this expansion?
- What thermodynamic pathways are involved?
- Is the process adiabatic, isothermal, or polytropic?

Analyzing the Expansion: Is it Isothermal, Adiabatic, or Otherwise?

Isothermal Expansion

In an isothermal process, the temperature remains constant:

$$ T_2 = T_1 = 600\, \mathrm{K} $$

Applying the ideal gas law at the final state:

$$ P_2 V_2 = n R T_2 $$

$$ P_2 = \frac{n R T_2}{V_2} = \frac{200.4 \times 8.314 \times 600}{5} $$

$$ P_2 \approx \frac{1,001,000}{5} \approx 200,200\, \mathrm{Pa} \approx 200.2\, \mathrm{kPa} $$

Implication: The pressure drops from 1000 kPa to approximately 200.2 kPa during the expansion if the process is perfectly isothermal.

Work Done (W): For an isothermal expansion:

$$ W = n R T \ln \left(\frac{V_2}{V_1} \right) $$

$$ W = 200.4 \times 8.314 \times 600 \times \ln 5 $$

$$ W \approx 1,001,000 \times 1.609 \approx 1.61 \times 10^6\, \mathrm{J} $$

This indicates a significant amount of work is done by the gas during expansion.

Adiabatic Expansion

In an adiabatic process, no heat exchange occurs with the surroundings:

$$ P V^\gamma = \text{constant} $$

where $\gamma = \frac{C_p}{C_v}$ (the heat capacity ratio). For diatomic gases like nitrogen or oxygen, $\gamma \approx 1.4$.

Using the adiabatic relation:

$$ \frac{T_2}{T_1} = \left(\frac{V_1}{V_2} \right)^{\gamma - 1} $$

$$ T_2 = 600 \times \left(\frac{1}{5} \right)^{0.4} $$

$$ T_2 \approx 600 \times 0.724 \approx 434.4\, \mathrm{K} $$

Final Pressure:

$$ P_2 = P_1 \left(\frac{V_1}{V_2} \right)^{\gamma} $$

$$ P_2 = 1000\, \mathrm{kPa} \times \left(\frac{1}{5} \right)^{1.4} $$

$$ P_2 \approx 1000 \times 0.114 \approx 114\, \mathrm{kPa} $$

Work Done:

$$ W = \frac{n R (T_1 - T_2)}{\gamma - 1} $$

$$ W \approx \frac{200.4 \times 8.314 \times (600 - 434.4)}{0.4} $$

$$ W \approx \frac{1,001,000 \times 165.6}{0.4} \approx 413 \times 10^6\, \mathrm{J} $$

The adiabatic process results in a larger temperature drop and lower final pressure compared to the isothermal case.

Implications of the Thermodynamic Pathway

The choice of process significantly influences the final states and the amount of work involved:

- Isothermal expansion entails heat absorption from the surroundings to maintain temperature, resulting in high work output.

- Adiabatic expansion occurs without heat exchange, leading to cooling and lower final pressure.

In real-world applications, the actual process may be somewhere between these idealized extremes, influenced by heat transfer rates, process duration, and system constraints.

Practical Significance and Applications

Understanding such expansion processes is critical in several fields:

1. Internal Combustion Engines: The expansion of gases during power strokes can be modeled similarly to ideal gas expansions, informing engine efficiency and design.

2. Gas Turbines and Engines: Controlled adiabatic expansions generate work efficiently, crucial for power generation.

3. Chemical and Process Industries: Managing gas expansion and compression processes optimizes reactions, energy consumption, and safety.

4. Thermodynamic Cycles: The Carnot, Otto, and Diesel cycles incorporate such expansion steps, with efficiency heavily dependent on the thermodynamic path.

Environmental and Energy Considerations

The expansion process directly impacts energy efficiency and environmental footprint:

- Energy Conversion Efficiency: The amount of work extracted during expansion influences the overall efficiency of turbines and engines.

- Heat Management: In real systems, minimizing heat loss or unwanted heat transfer can optimize performance.

- Carbon Footprint: Efficient energy conversion reduces fuel consumption and emissions.

Advanced Analytical Perspectives

Entropy Change

For ideal gases, the entropy change during expansion from initial to final state:

$$\Delta S = n C_v \ln \left(\frac{T_2}{T_1} \right) + n R \ln \left(\frac{V_2}{V_1} \right)$$

- Isothermal process: $\Delta S = n R \ln 5 \approx 200.4 \times 8.314 \times 1.609 \approx 2.68 \times 10^3\, \mathrm{J/K}$

- Adiabatic process: $\Delta S = 0$ (since it is reversible and adiabatic)

The entropy change indicates the degree of disorder introduced by the process, with implications for reversibility and irreversibility.

Conclusion

The expansion of one cubic meter of an ideal gas at 600 K and 1000 kPa to five times its initial volume exemplifies fundamental thermodynamic principles. Whether the process is idealized as isothermal or adiabatic, each pathway offers insights into how gases perform under different conditions, influencing engineering design, energy efficiency, and environmental impact.

By meticulously analyzing initial conditions, thermodynamic relationships, and the implications of various process pathways, engineers and scientists can better harness the behavior of gases for technological advancement. This scenario underscores the importance of thermodynamics as a predictive and design tool in a broad spectrum of scientific and industrial applications, emphasizing

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