MA 2.00 –mol Sample Of Helium Gas Initially At 300K , And 0.400atm Is Compressed Isothermally To 1.20atm

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Introduction

The behavior of gases under various conditions is a fundamental aspect of thermodynamics and physical chemistry. When a gas undergoes a transformation, understanding the relationship between pressure, volume, temperature, and amount of substance is crucial. In this context, examining the isothermal compression of a helium gas sample provides insights into the principles of ideal gas behavior, work done during compression, and related thermodynamic parameters. This article explores the process where 2.00 mol of helium gas, initially at 300 K and 0.400 atm, is compressed isothermally to a final pressure of 1.20 atm, analyzing the calculations, concepts, and implications involved.

Understanding the Initial Conditions

Given Data

- Number of moles of helium, $n = 2.00 \text{ mol}$
- Initial temperature, $T_1 = 300 \text{ K}$
- Initial pressure, $P_1 = 0.400 \text{ atm}$
- Final pressure, $P_2 = 1.20 \text{ atm}$
- Process: Isothermal (constant temperature)

Importance of Helium as an Ideal Gas

Helium, a noble gas, exhibits behavior closely approximating that of an ideal gas over a wide range of conditions. Its monatomic nature simplifies calculations because its internal energy depends only on temperature, and interactions between particles are negligible at typical laboratory conditions. This makes helium an excellent model for studying ideal gas behavior during compression and expansion processes.

Applying the Ideal Gas Law

Fundamental Equation

The ideal gas law relates pressure, volume, temperature, and the amount of gas:

$$
PV = nRT
$$

Where:
- P = pressure
- V = volume
- n = number of moles
- R = ideal gas constant ($0.082057 \text{ L·atm·mol}^{-1}\text{·K}^{-1}$)
- T = temperature in Kelvin

Calculating Initial and Final Volumes

Since the process is isothermal, T remains constant. Using the ideal gas law:

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

$$
V_2 = \frac{n R T_2}{P_2}
$$

But because $T_1 = T_2$, the relation simplifies to:

$$
\frac{V_1}{P_1} = \frac{V_2}{P_2}
$$

Calculating V_1:

$$
V_1 = \frac{(2.00)(0.082057)(300)}{0.400}
$$

$$
V_1 \approx \frac{(2.00)(24.6171)}{0.400} \approx \frac{49.2342}{0.400} \approx 123.09 \text{ L}
$$

Similarly, the final volume V_2:

$$
V_2 = \frac{(2.00)(0.082057)(300)}{1.20}
$$

$$
V_2 \approx \frac{49.2342}{1.20} \approx 41.03 \text{ L}
$$

This confirms that volume decreases as pressure increases during the isothermal process.

Work Done During Isothermal Compression

Theoretical Background

In an isothermal process, the temperature remains constant, and the work done on the gas can be calculated using:

$$
W = nRT \ln \left(\frac{V_1}{V_2} \right)
$$

Alternatively, since $PV = nRT$, the work can also be expressed in terms of pressure:

$$
W = P_1 V_1 \ln \left(\frac{P_2}{P_1} \right)
$$

This formula is often preferred because pressures are typically easier to measure or specify.

Calculating Work Done

Using:

$$
W = P_1 V_1 \ln \left(\frac{P_2}{P_1} \right)
$$

Substituting known values:

$$
W = (0.400 \text{ atm}) \times 123.09 \text{ L} \times \ln \left(\frac{1.20}{0.400} \right)
$$

Calculate the natural log:

$$
\ln(3) \approx 1.0986
$$

Calculate $P_1 V_1$:

$$
0.400 \times 123.09 \approx 49.24 \text{ L·atm}
$$

Therefore,

$$
W \approx 49.24 \times 1.0986 \approx 54.07 \text{ L·atm}
$$

To convert this to Joules:

$$
1 \text{ L·atm} = 101.3 \text{ J}
$$

Thus,

$$
W \approx 54.07 \times 101.3 \approx 5474.8 \text{ J}
$$

Since work is done on the gas during compression, the work value is positive in the context of energy input:

$$
\boxed{
W \approx 5475 \text{ J}
}
$$

This indicates that approximately 5.475 kJ of work is required to compress the helium gas isothermally from 0.400 atm to 1.20 atm.

Thermodynamic Implications of the Compression

Heat Exchange in Isothermal Process

In an ideal gas undergoing an isothermal process, the internal energy change (ΔU) is zero because internal energy depends solely on temperature:

$$
\Delta U = 0
$$

Given the first law of thermodynamics:

$$
\Delta U = Q - W
$$

Where:

- Q = heat exchanged with surroundings
- W = work done by the system

Rearranged:

$$
Q = W
$$

Since work is done on the gas during compression, the heat exchanged with surroundings is approximately 5.475 kJ absorbed by the gas:

$$
Q \approx 5475 \text{ J}
$$

This heat absorption maintains the temperature constant during compression.

Entropy Change of the System

The change in entropy (ΔS) for an ideal gas during an isothermal process is:

$$
\Delta S = n R \ln \left(\frac{V_2}{V_1} \right) = - n R \ln \left(\frac{V_1}{V_2} \right)
$$

Using the volumes calculated earlier:

$$
\Delta S = 2.00 \times 0.082057 \times \ln \left(\frac{123.09}{41.03} \right)
$$

Calculate the ratio:

$$
\frac{123.09}{41.03} \approx 3
$$

Calculate the natural log:

$$
\ln(3) \approx 1.0986
$$

Hence:

$$
\Delta S \approx 2.00 \times 0.082057 \times 1.0986 \approx 0.180 \text{ J/K}
$$

The entropy increases by approximately 0.180 J/K due to the increase in volume during expansion, or equivalently, the decrease during compression.

Comparison With Real Gas Behavior and Limitations

While the ideal gas law provides a convenient model, real gases deviate under high pressures or low temperatures due to intermolecular forces and finite particle size. Helium, being monatomic and with weak interatomic forces, exhibits minimal deviations, especially within the conditions discussed.

However, for precise applications or extreme conditions, real gas equations such as the Van der Waals equation should be employed:

$$
\left(P + \frac{a}{V^2} \right) (V - b) = nRT
$$

Where:
- a accounts for attractive forces
- b accounts for the finite volume of particles

For helium, these corrections are negligible at moderate pressures, validating the ideal gas assumptions used here.

Practical Applications and Significance

Understanding the thermodynamics of helium compression has real-world applications:

- Cryogenics: Helium is extensively used in cryogenic applications, including cooling superconducting magnets.
- Gas Storage and Transportation: Knowledge of compression work informs energy requirements for liquefying or pressurizing helium.
- Industrial Processes: Helium's inertness and low boiling point make it ideal for leak detection and inert atmospheres.

The calculations demonstrate the energy input needed for compression and the associated heat management, critical for designing efficient systems.

Conclusion

The isothermal compression of

Frequently Asked Questions

What is the initial state of the helium gas sample in

terms of temperature and pressure?

The initial state of the helium gas is at a temperature of 300 K and a pressure of 0.400 atm.

What is the process occurring when the helium gas is compressed from 0.400 atm to 1.20 atm?

The process is an isothermal compression, meaning the temperature remains constant at 300 K during compression.

How much work is done on the helium gas during the isothermal compression from 0.400 atm to 1.20 atm?

The work done can be calculated using the formula W = nRT ln(P2/P1), which results in approximately 19.1 Joules.

What is the change in internal energy of the helium gas during the isothermal process?

Since the process is isothermal for an ideal gas, the internal energy change is zero, $\Delta U = 0$.

How can we calculate the final volume of the helium gas after compression?

Using the ideal gas law, the final volume V2 = (nRT)/P2. Given the initial conditions, V2 can be calculated accordingly.

Why is the internal energy of the helium gas unchanged during isothermal compression?

Because for an ideal gas, internal energy depends only on temperature, which remains constant during an isothermal process.

What is the significance of using the ideal gas law in analyzing this helium compression process?

The ideal gas law allows us to relate pressure, volume, and temperature, simplifying calculations and understanding the behavior of the helium gas during compression.

Additional Resources

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Introduction

The study of gas behavior under varying conditions has long been a cornerstone of thermodynamics and physical chemistry. Among the simplest yet most informative models is the ideal gas law, which provides a foundational understanding of how gases respond to changes in pressure, volume, temperature, and quantity. Helium, with its monatomic structure and inertness, serves as an ideal candidate for such investigations. This article delves into a specific scenario: a MA 2.00-mol sample of helium gas initially at 300K and 0.400 atm, compressed isothermally to 1.20 atm. By examining this process, we explore the principles of ideal gas behavior, the thermodynamic implications of isothermal compression, and the broader significance of such studies in scientific and engineering contexts.

Background and Significance

The Choice of Helium as the Subject

Helium's unique properties make it particularly suitable for thermodynamic analysis:

- Monatomic Nature: Helium consists of single atoms, simplifying the internal energy considerations since it has no vibrational or rotational modes.
- Inertness: Its chemical inertness ensures that reactions do not complicate the physical process.
- Low Mass and High Diffusivity: These properties facilitate rapid thermal conduction and energy exchange, aligning well with ideal gas assumptions.

Relevance of Isothermal Processes

An isothermal process maintains constant temperature, which implies that any work done on or by the gas is balanced by heat exchange with the surroundings. In practical applications, understanding such processes informs the design of engines, refrigerators, and other thermodynamic devices where temperature stability is crucial.

Theoretical Framework

Ideal Gas Law and Its Application

The ideal gas law is expressed as:

$$ PV = nRT $$

where:

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

Given the initial conditions, the laws of thermodynamics predict the behavior of the gas during compression.

Initial Conditions and Calculations

Initial State

- Moles of helium, $n = 2.00\, \text{mol}$
- Temperature, $T_i = 300\, \text{K}$
- Initial pressure, $P_i = 0.400\, \text{atm}$

Using the ideal gas law to find initial volume:

$$V_i = \frac{nRT_i}{P_i}$$

Convert pressure to SI units:

$$P_i = 0.400\, \text{atm} \times 101.325\, \text{kPa/atm} = 40.53\, \text{kPa}$$

Calculate V_i:

$$V_i = \frac{2.00\, \text{mol} \times 8.314\, \text{J/mol·K} \times 300\, \text{K}}{40.53 \times 10^3\, \text{Pa}}$$

$$V_i = \frac{2.00 \times 8.314 \times 300}{40530}$$

$$V_i \approx \frac{4988.4}{40530} \approx 0.123\, \text{m}^3$$

The Compression Process

Isothermal Compression Dynamics

During an isothermal process:

- Temperature remains constant ($T = T_i = T_f$)
- The internal energy change (ΔU) for an ideal monatomic gas is zero because internal energy depends only on temperature.

The process involves reducing the volume:

$$V_f = \frac{nRT}{P_f}$$

Given the final pressure:

$$P_f = 1.20\, \text{atm} = 121.59\, \text{kPa}$$

Calculate final volume:

$$V_f = \frac{2.00 \times 8.314 \times 300}{121.59 \times 10^3}$$

$$V_f = \frac{4988.4}{121590} \approx 0.041\, \text{m}^3$$

This indicates the volume decreases by approximately 66%, demonstrating significant compression.

Thermodynamic Analysis

Work Done During Isothermal Compression

The work W performed on the gas during an isothermal process is:

$$W = nRT \ln \left(\frac{V_i}{V_f} \right)$$

Alternatively, expressed in terms of pressures:

$$W = nRT \ln \left(\frac{P_f}{P_i} \right)$$

Calculate W:

$$W = 2.00 \times 8.314 \times 300 \times \ln \left(\frac{1.20}{0.400} \right)$$

$$W = 4988.4 \times \ln (3)$$

$$W \approx 4988.4 \times 1.0986 \approx 5482\, \text{J}$$

Since work is done on the gas during compression, this is considered positive from the perspective of the surroundings.

Heat Exchange with the Environment

In an ideal isothermal process:

$$Q = W$$

This means the environment must supply approximately 5482 J of heat to compensate for the work done on the gas, maintaining constant temperature.

Broader Implications and Practical Considerations

Real-World Deviations

While the ideal gas law offers a solid approximation, real gases exhibit deviations especially at high pressures or low temperatures. For helium at the given conditions, deviations are minimal, but in practical applications, corrections via van der Waals or other equations of state may be necessary.

Applications in Engineering and Science

- Cryogenics: Helium's properties are exploited in cooling systems, and understanding its thermodynamic behavior guides efficient design.
- Gas Compression and Storage: Insights into isothermal compression inform storage strategies for gases under pressure.
- Fundamental Research: Experiments involving controlled compression of inert gases serve as testbeds for thermodynamic theories and models.

Environmental and Safety Considerations

Handling helium, especially under high pressure, requires proper safety protocols:

- Pressure Vessel Integrity: Ensuring containers withstand compression pressures.
- Leak Prevention: Helium's small atomic size makes it prone to leakage;

robust seals are essential.
- Environmental Impact: Helium is a finite resource; responsible usage and recycling are encouraged.

Future Directions and Research Opportunities

Further investigations could explore:

- Non-ideal behaviors at higher pressures
- Dynamic thermodynamic processes involving rapid compression or expansion
- Energy efficiency optimization in compression systems
- Use of real-time sensors to monitor gas behavior during compression

Advancements in computational modeling and experimental techniques promise deeper insights into the nuanced behavior of gases under various thermodynamic conditions.

Conclusion

The case study of MA 2.00-mol sample of helium gas initially at 300K and 0.400 atm, compressed isothermally to 1.20 atm exemplifies fundamental principles of thermodynamics. Through detailed calculations, we observe that the process involves a substantial decrease in volume, requiring approximately 5482 Joules of heat input to maintain constant temperature. Helium's simplicity and inertness make it an ideal model for understanding ideal gas behavior, with implications spanning scientific research, industrial applications, and environmental management. As thermodynamic modeling advances, such detailed analyses remain vital for optimizing processes and expanding our understanding of gas behavior under various conditions.

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Note: All calculations assume ideal behavior and are approximations for educational purposes.

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