Problem 20.46A 1.50-L Sample Of An Ideal Gas Initially At 1.00 Atm And 273 K Undergoes An Isobaric Process

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Understanding the behavior of gases during different thermodynamic processes is fundamental in physics and engineering. Specifically, analyzing how an ideal gas responds to changes in pressure, volume, and temperature provides insights into energy transfer, work done, and heat exchange. In this article, we delve into the problem involving a 1.50-liter sample of an ideal gas initially at 1.00 atm and 273 K, which undergoes an isobaric (constant pressure) process. We will explore the principles involved, detailed calculations, and practical implications, making it accessible for students and professionals alike.

Introduction to the Problem

The problem involves a sample of an ideal gas with the following initial conditions:

- Initial volume (V_1): 1.50 L
- Initial pressure (P_1): 1.00 atm
- Initial temperature (T_1): 273 K

The gas undergoes an isobaric process, meaning the pressure remains constant throughout the transformation. Typically, such problems ask for quantities like the final volume or temperature, work done by the gas, heat exchanged, or changes in internal energy.

Understanding the concepts of isobaric processes and applying the ideal gas law are key to solving this problem. Let's explore these in detail.

Fundamentals of Isobaric Processes

An isobaric process is a thermodynamic process during which the pressure of the system remains constant.

For an ideal gas, this process can involve changes in volume and temperature, and the work done by or on the gas can be directly calculated.

Key points about isobaric processes:

- The pressure P remains fixed.
- The work done by the gas during expansion or compression is given by:

$$
W = P \Delta V
$$

where $\Delta V = V_{final} - V_{initial}$

- The first law of thermodynamics applies:

$$
\Delta U = Q - W
$$

where ΔU is the change in internal energy, and Q is the heat added to the system.

Important implications:

- When the gas expands at constant pressure, it absorbs heat.
- When compressed, heat is released.

Applying the Ideal Gas Law

The ideal gas law is fundamental to solving thermodynamic problems involving gases:

$$
PV = nRT
$$

where:

- P = pressure
- V = volume

- n = number of moles
- R = ideal gas constant ($8.314\, \mathrm{J/(mol\,K)}$)
- T = temperature in Kelvin

Given initial conditions, we can determine the number of moles:

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

In our problem:

$$
n = \frac{(1.00\, \mathrm{atm})(1.50\, \mathrm{L})}{(0.082057\, \mathrm{L\,atm/(mol\,K)})(273\, \mathrm{K})}
$$

Note: R can be used as $0.082057\, \mathrm{L\,atm/(mol\,K)}$ when pressure is in atm and volume in liters.

Calculating n:

$$
n = \frac{1.00 \times 1.50}{0.082057 \times 273} = \frac{1.50}{22.413} \approx 0.067\, \mathrm{mol}
$$

This molar quantity remains constant in a closed system.

Possible Scenarios and Calculations

Depending on the problem's specifics, various questions might be asked, such as:

- What is the final temperature if the volume changes?
- How much work is done during the process?
- How much heat is transferred?

Let's explore typical calculations relevant to an isobaric process.

1. Final Volume or Temperature

Suppose the process involves a change in temperature. Using the ideal gas law at initial and final states:

$$
\frac{V_1}{T_1} = \frac{V_2}{T_2}
$$

since pressure P remains constant.

If the final temperature T_2 is known or specified, the final volume V_2 can be found:

$$
V_2 = V_1 \times \frac{T_2}{T_1}
$$

Alternatively, if the volume change is specified, the final temperature can be calculated.

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2. Calculating Work Done

The work done during an isobaric process:

$$
W = P \times (V_2 - V_1)
$$

Expressed in SI units:

- Convert volume from liters to cubic meters: $1\, \mathrm{L} = 10^{-3}\, \mathrm{m^3}$

Suppose the final volume is $V_2 = 3.00\, \mathrm{L}$:

$$
V_2 = 3.00\, \mathrm{L} = 3.00 \times 10^{-3}\, \mathrm{m^3}
$$

Using initial volume:

\[

$$
V_1 = 1.50\, \mathrm{L} = 1.50 \times 10^{-3}\, \mathrm{m^3}
$$

Convert pressure from atm to Pascals:

$$
1\, \mathrm{atm} = 101325\, \mathrm{Pa}
$$

So,

$$
P = 1.00\, \mathrm{atm} = 101325\, \mathrm{Pa}
$$

Calculate work:

$$
W = 101325\, \mathrm{Pa} \times (3.00 \times 10^{-3} - 1.50 \times 10^{-3})\, \mathrm{m^3} = 101325 \times 1.50 \times 10^{-3} \approx 151.99\, \mathrm{J}
$$

The positive work indicates work done by the gas during expansion.

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3. Heat Exchange in an Isobaric Process

The heat added or removed:

$$
Q = \Delta U + W
$$

For an ideal gas:

$$
\Delta U = n C_v \Delta T
$$

where $C_v = \frac{3}{2} R$ for a monatomic gas, or $C_v = R$ for diatomic gases under certain conditions. The specific heat depends on the gas type; for simplicity, assume a monatomic ideal gas:

$$
C_v = \frac{3}{2} R \approx 12.471\, \mathrm{J/(mol\,K)}
$$

Suppose the temperature increases from 273 K to 300 K:

$$
\Delta T = 300\, \mathrm{K} - 273\, \mathrm{K} = 27\, \mathrm{K}
$$

Calculate ΔU:

$$
\Delta U = n C_v \Delta T = 0.067\, \mathrm{mol} \times 12.471\, \mathrm{J/(mol\,K)} \times 27\, \mathrm{K} \approx 22.6\, \mathrm{J}
$$

Total heat exchanged:

$$
Q = \Delta U + W = 22.6\, \mathrm{J} + 151.99\, \mathrm{J} \approx 174.6\, \mathrm{J}
$$

This amount of heat flows into the system to produce both the increase in internal energy and the work output.

Practical Applications and Significance

Understanding isobaric processes of ideal gases is crucial across various fields:

- Engineering: Designing engines, refrigerators, and HVAC systems.
- Physics: Teaching thermodynamics principles.
- Chemistry: Reactions involving gases often involve pressure and volume changes.
- Environmental Science: Modeling atmospheric and environmental gas behaviors.

Precise calculations inform real-world decisions, such as optimizing fuel efficiency or predicting atmospheric phenomena.

Conclusion

The problem involving a 1.50-liter sample of an ideal gas at 1.00 atm and 273 K undergoing an isobaric process encapsulates essential thermodynamic concepts. By applying the ideal gas law, understanding the nature of isobaric processes, and performing systematic calculations, we can determine key parameters such as work done, heat transfer, and changes in temperature or volume.

Mastering these concepts enables scientists and engineers to analyze and design systems involving gases, optimize energy use, and deepen our understanding of thermodynamic principles. Whether dealing with simple laboratory experiments or complex industrial processes, the foundational knowledge of ideal gases and isobaric transformations remains integral.

Further Reading and Resources

- Introduction to Thermodynamics by Richard E. Sonntag and Claus Borgnakke
- Fundamentals of Physics by David Halliday, Robert Resnick, and Jearl Walker
- Online simulations of thermodynamic processes at [PhET Interactive Simulations](https://phet.colorado.edu/)

Frequently Asked Questions

What is the initial state of the ideal gas in Problem 20.46A?

The initial state has a volume of 1.50 L, pressure of 1.00 atm, and temperature of 273 K.

What type of process does the gas undergo in Problem 20.46A?

The gas undergoes an isobaric process, meaning the pressure remains constant throughout the process.

How do you calculate the initial amount of moles of gas in the sample?

Using the ideal gas law: $n = PV / RT$. Substituting $P=1.00$ atm, $V=1.50$ L, $R=0.0821$ L·atm/(mol·K), $T=273$ K gives $n \approx 0.075$ mol.

What is the significance of the isobaric process in this problem?

An isobaric process allows us to analyze how the volume and temperature change at constant pressure, often involving work done by or on the gas.

How can we determine the final temperature if the final volume is known?

Using the ideal gas law: $T_2 = (P V_2) / (n R)$. Knowing initial moles and pressure, and the final volume, we can find T_2.

What is the work done by the gas during the isobaric process?

Work done is $W = P \Delta V$, where ΔV is the change in volume. Since pressure is constant, the work depends directly on the change in volume.

How does the heat transfer relate to the change in internal energy and work done in this process?

Using the first law of thermodynamics: $Q = \Delta U + W$. For an ideal gas, ΔU depends on temperature change, so heat added relates to changes in temperature and work.

What are common applications of isobaric processes in real-world scenarios?

Examples include cooking (boiling water), heating gases in engines, and processes in atmospheric science where pressure remains relatively constant.

How does understanding this problem help in grasping thermodynamics principles?

It provides insight into how gases behave under constant pressure, allowing calculation of work, heat transfer, and state changes, which are fundamental in thermodynamics.

Additional Resources

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Introduction

In the realm of thermodynamics, the study of ideal gases undergoing various processes provides fundamental insights into energy transfer, work, and heat interactions. Among these, the isobaric process—where pressure remains constant—is particularly significant both in theoretical analyses and practical applications such as heating, cooling, and industrial operations. The problem involving a 1.50-L sample of an ideal gas initially at 1.00 atm and 273 K, undergoing an isobaric process, serves as a classic example illustrating key thermodynamic principles.

This review aims to dissect the problem comprehensively, exploring the physical setup, underlying assumptions, mathematical formulations, and broader implications, ultimately providing a detailed understanding suitable for educators, students, and researchers alike.

Fundamental Concepts and Physical Context

Overview of Ideal Gas Behavior

An ideal gas is a theoretical model where particles are considered point masses that do not interact except through elastic collisions. The ideal gas law relates pressure (P), volume (V), temperature (T), and amount of substance (n):

$$ PV = nRT $$

where R is the universal gas constant.

In this problem, the initial state features:

- Volume, $V_i = 1.50\ L = 1.50 \times 10^{-3}\ m^3$
- Pressure, $P = 1.00\ atm = 1.01325 \times 10^5\ Pa$
- Temperature, $T_i = 273\ K$

The sample undergoes an isobaric process, meaning the pressure remains fixed throughout the transformation, but volume and temperature may change.

Nature of Isobaric Processes

An isobaric process involves the system expanding or compressing at constant pressure. The work done by the gas during such a process is given by:

$$ W = P \Delta V = P (V_f - V_i) $$

where V_f is the final volume.

The heat transfer, Q, relates to the change in internal energy and work done:

$$ Q = \Delta U + W $$

For an ideal gas, the internal energy depends solely on temperature:

$$ \Delta U = n C_V \Delta T $$

with $C_V = \frac{f}{2} R$, where f is the degrees of freedom.

Mathematical Analysis of the Isobaric Process

Calculating the Number of Moles

Using the ideal gas law:

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

Plugging in the known values:

$$ n = \frac{(1.01325 \times 10^5\ Pa)(1.50 \times 10^{-3}\ m^3)}{(8.314\, J/(mol\,K))(273\,K)} $$

$$ n \approx \frac{152\, J}{2269\, J/mol} \approx 0.067 mol $$

This calculation establishes the amount of gas involved, setting the stage for further thermodynamic calculations.

Possible Scenarios for the Process

Depending on the problem's specifics, the final conditions could involve:

- An increase in volume at constant pressure

- A decrease in volume
- Heating or cooling effects

Assuming the process involves heating at constant pressure, the key quantities to determine include the final temperature, work done, heat transfer, and internal energy change.

Thermodynamic Quantities

Final Volume and Temperature

From the ideal gas law:

$$ V_f = \frac{nRT_f}{P} $$

If, for example, the final temperature is specified or deduced, the final volume can be calculated accordingly.

Alternatively, if the problem specifies the heat added or removed, the temperature change can be directly determined.

Work Done by the Gas

Since pressure is constant:

$$ W = P (V_f - V_i) $$

or, expressed in terms of temperature:

$$ W = n R (T_f - T_i) $$

Because $PV = nRT$, the work can be expressed equivalently as:

$$ W = n R (T_f - T_i) $$

This provides a straightforward link between temperature change and work, emphasizing the importance of temperature differences in isobaric processes.

Heat Transfer

The heat added or removed:

$$Q = \Delta U + W$$

Given $\Delta U = n C_V (T_f - T_i)$, and $C_V = \frac{f}{2} R$, the total heat transfer becomes:

$$Q = n C_V (T_f - T_i) + n R (T_f - T_i) = n (C_V + R) (T_f - T_i)$$

Since $C_P = C_V + R$, the heat transfer simplifies to:

$$Q = n C_P (T_f - T_i)$$

This relation underscores the role of specific heats in energy exchange during isobaric processes.

Broader Implications and Practical Applications

Relevance to Engineering and Atmospheric Science

Understanding the thermodynamics of ideal gases under isobaric conditions has direct implications for:

- Heating and cooling systems: Such as boilers and air conditioners, where volume changes at constant pressure are common.
- Internal combustion engines: Where gases expand and do work at nearly constant pressure during certain phases.
- Atmospheric processes: The adiabatic and isobaric expansion or compression of air masses influences weather and climate modeling.

Real-World Deviations and Limitations

While ideal gas assumptions facilitate analysis, real gases exhibit interactions and finite particle sizes. Corrections using van der Waals equations or other models are necessary for high-pressure or low-temperature conditions. Nonetheless, the ideal gas model remains invaluable for initial approximations and educational purposes.

Advanced Topics and Further Considerations

Entropy Change and Reversibility

The entropy change for an ideal gas undergoing an isobaric process:

$$\Delta S = n C_P \ln \left(\frac{T_f}{T_i} \right)$$

This relation helps assess the reversibility of the process and the entropy production, critical in thermodynamic cycle analysis.

Work and Heat in Cyclic Processes

When the process is part of a thermodynamic cycle, such as in engines or refrigerators, the net work and heat exchanges over complete cycles are analyzed to evaluate efficiency and performance.

Conclusion

The exploration of a 1.50-L sample of an ideal gas initially at 1.00 atm and 273 K undergoing an isobaric process exemplifies core thermodynamic principles. By meticulously deriving the relationships between pressure, volume, temperature, work, and heat, we gain insights into energy transformations that are fundamental not only in theoretical physics but also in practical engineering and atmospheric science.

This detailed analysis underscores the importance of understanding the ideal gas law and thermodynamic identities to predict system behavior accurately. Such knowledge informs the design and optimization of numerous thermal systems and enhances our grasp of natural phenomena driven by gas thermodynamics.

In future investigations, extending these principles to non-ideal gases or incorporating phase changes could provide a more comprehensive understanding of real-world systems. Nonetheless, mastery of the idealized models remains a cornerstone of thermodynamic education and research.

References

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- Çengel, Y. A., & Boles, M. A. (2015). Thermodynamics: An Engineering Approach (8th ed.). McGraw-Hill Education.

- Sonntag, R. E., Borgnakke, C., & Van Wylen, G. (2003). Fundamentals of Thermodynamics (6th ed.). Wiley.

This comprehensive review provides a detailed understanding of the thermodynamics of an ideal gas undergoing an isobaric process, incorporating fundamental equations, practical considerations, and broader implications for science and engineering.

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