Given That The Vapor Pressure Of Water Is 17.54 Torr At 20 C, Calculate The Vapor-pressure Lowering Of

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Understanding vapor pressure and its implications in chemistry is fundamental for students and professionals working with liquids, solutions, and phase equilibria. The vapor-pressure lowering phenomenon plays a crucial role in processes such as boiling point elevation, freezing point depression, and the behavior of solutions. In this comprehensive guide, we will explore how to calculate vapor-pressure lowering given specific data, focusing on the vapor pressure of water at 20°C. We will break down the concepts, formulas, and step-by-step calculations to enhance your understanding of this important aspect of solution chemistry.

Understanding Vapor Pressure and Vapor-Pressure Lowering

What Is Vapor Pressure?

Vapor pressure is the pressure exerted by a vapor in equilibrium with its liquid phase at a given temperature. It reflects the tendency of molecules to escape from the liquid into the vapor phase. The higher the vapor pressure at a specific temperature, the more volatile the liquid.

Key points about vapor pressure:
- It is temperature-dependent: increases with rising temperature.
- It indicates volatility: liquids with higher vapor pressures evaporate more readily.
- It is essential in determining boiling points: a liquid boils when its vapor pressure equals atmospheric pressure.

What Is Vapor-Pressure Lowering?

When a non-volatile solute is dissolved in a solvent, the vapor pressure of the solvent decreases relative to the pure solvent. This phenomenon is known as vapor-pressure lowering or vapor-pressure depression.

Why does this occur?
- The solute particles occupy space at the surface, reducing the number of solvent molecules escaping into the vapor phase.

- The result is a lower vapor pressure compared to the pure solvent at the same temperature.

Implications:
- It explains colligative properties such as boiling point elevation and freezing point depression.
- It is quantitatively described by Raoult’s Law.

Raoult’s Law and Vapor-Pressure Lowering

Raoult’s Law provides the foundation for calculating vapor-pressure lowering:

$$
\Delta P_{vap} = P_{pure} - P_{solution}
$$

or equivalently,

$$
P_{solution} = X_{solvent} \times P_{pure}
$$

where:
- P_{pure} is the vapor pressure of the pure solvent at a given temperature.
- $P_{solution}$ is the vapor pressure of the solvent in the solution.
- $X_{solvent}$ is the mole fraction of the solvent in the solution.
- ΔP_{vap} is the vapor-pressure lowering.

Key relation:

$$
\Delta P_{vap} = X_{solute} \times P_{pure}
$$

assuming ideal solutions and dilute solutions where the mole fraction of solute is small.

Given Data and Problem Restatement

The problem states:

- The vapor pressure of water at 20°C is 17.54 Torr.
- We are asked to calculate the vapor-pressure lowering (ΔP_{vap})

when a certain solute is dissolved in water.

However, the problem as presented does not specify the amount of solute or the concentration of the solution. Typically, to compute vapor-pressure lowering, you need:

- The molar amount or molality of the solute.
- The molar mass of the solute.
- The total amount of solvent (water).

In the absence of explicit data, we will proceed with a typical example to illustrate how the calculation is performed. This example assumes a dilute solution with known molality or mole fraction.

Step-by-Step Calculation of Vapor-Pressure Lowering

1. Establish the Data and Assumptions

Suppose:
- The solution contains 1 mol of a non-volatile solute dissolved in 1000 g (1 kg) of water.
- Molar mass of water = 18.015 g/mol.
- Vapor pressure of pure water at 20°C, P_{pure} = 17.54 Torr.

Calculate:
- Mole fraction of water (X_{water}).
- Vapor-pressure lowering (ΔP_{vap}).

2. Calculate the Moles of Water and Solute

- Moles of water:

$$
n_{water} = \frac{1000\,g}{18.015\,g/mol} \approx 55.5\,mol
$$

- Moles of solute:

$$
n_{solute} = 1\,mol
$$

3. Determine Mole Fraction of Water (X_{water})

Total moles:

$$
n_{total} = n_{water} + n_{solute} = 55.5 + 1 = 56.5\,mol
$$

Mole fraction of water:

$$
X_{water} = \frac{n_{water}}{n_{total}} = \frac{55.5}{56.5} \approx 0.9823
$$

4. Calculate Vapor-Pressure Lowering (ΔP_{vap})

Raoult's Law:

$$
P_{solution} = X_{water} \times P_{pure} = 0.9823 \times 17.54\, Torr \approx 17.22\, Torr
$$

Vapor-pressure lowering:

$$
\Delta P_{vap} = P_{pure} - P_{solution} = 17.54\, Torr - 17.22\, Torr = 0.32\, Torr
$$

Result: The vapor-pressure lowering is approximately 0.32 Torr for this example.

General Formula and Variations

The calculation depends on the molal or molar concentration of the solute and the mole fraction. The general steps involve:

- Determining the mole fraction of the solvent.
- Applying Raoult's Law to find the new vapor pressure.
- Calculating the difference between the pure solvent vapor pressure and the solution vapor pressure.

For dilute solutions, the vapor-pressure lowering can also be approximated using molality (m) and the molar mass of the solvent:

$$
\Delta P_{vap} = i \times K_{b} \times m
$$

where:
- i is the van’t Hoff factor.
- K_{b} is the ebullioscopic constant (or similar constant depending on context).
- m is molality.

Note: The molality-based formula is mainly used for boiling point elevation but can be related to vapor pressure lowering through colligative properties.

Real-World Applications of Vapor-Pressure Lowering Calculations

Understanding vapor-pressure lowering has practical implications in various fields:

- **Pharmaceuticals:** Formulating solutions to control evaporation.
- **Chemical Engineering:** Designing distillation and separation processes.
- **Food Industry:** Preserving products by manipulating vapor pressures.
- **Environmental Science:** Studying evaporation rates and humidity control.

Summary and Key Takeaways

- Vapor-pressure lowering occurs when a non-volatile solute dissolves in a solvent, reducing the solvent’s vapor pressure.
- Raoult’s Law provides a quantitative basis for calculating vapor-pressure depression.
- The calculation involves knowing the mole fraction of the solvent, which depends on the amount of solute and solvent.
- In typical problems, assuming dilute solutions simplifies calculations.
- Real-world applications leverage these principles for controlling evaporation, boiling points, and solution behavior.

Conclusion

Calculating vapor-pressure lowering involves understanding the fundamental principles of solution chemistry and applying Raoult’s Law. By knowing the vapor pressure of the pure solvent and the composition of the solution, chemists can accurately determine how much the vapor pressure decreases due to solute addition. This knowledge is essential across scientific disciplines, from designing pharmaceuticals to optimizing industrial processes.

Always ensure you have complete data on solution composition to perform precise calculations. If specific molar concentrations or masses are provided, the calculation becomes straightforward. In cases where data is limited, making reasonable assumptions can help illustrate the process, as demonstrated in this example.

By mastering these calculations, you can better understand colligative properties and their significance in both theoretical and applied chemistry.

Frequently Asked Questions

What is vapor-pressure lowering in solutions?

Vapor-pressure lowering is the decrease in the vapor pressure of a solvent when a non-volatile solute is dissolved in it, due to the solute particles reducing the solvent molecules' escape tendency.

How is Raoult's law related to vapor-pressure lowering?

Raoult's law states that the vapor pressure of a solvent in a solution is proportional to its mole fraction, and the vapor-pressure lowering is the difference between the pure solvent's vapor pressure and the solution's vapor pressure, calculated using this law.

Given the vapor pressure of water at 20°C is 17.54 Torr, how do you calculate the vapor-pressure lowering if a solute is dissolved?

Vapor-pressure lowering (ΔP) is calculated as the difference between the vapor pressure of pure water and that of the solution, typically using $\Delta P = P° - P_{solution}$, where $P°$ is 17.54 Torr.

What additional information is needed to calculate the vapor-pressure lowering of water when a solute is added?

You need the mole fraction of water in the solution or the molality/molarity of the solute and the amount of solvent to determine the mole fraction and compute the vapor-pressure lowering.

How does temperature affect vapor-pressure lowering?

Temperature influences vapor pressure; as temperature increases, vapor pressure increases, which can affect the magnitude of vapor-pressure lowering in a solution, though the calculation method remains the same.

Can you demonstrate the calculation of vapor-pressure lowering with an example?

Yes. For example, if the mole fraction of water (X_w) is 0.9, then vapor-pressure lowering $\Delta P = P° \times (1 - X_w) = 17.54$ Torr $\times (1 - 0.9) = 1.754$ Torr.

What assumptions are made when calculating vapor-pressure lowering using Raoult's law?

It is assumed that the solution behaves ideally, the solute is non-volatile, and the interactions between solvent and solute molecules are similar to those between solvent molecules themselves.

Why is understanding vapor-pressure lowering important in chemistry?

It helps in understanding colligative properties, designing solutions, controlling evaporation processes, and determining molar masses of solutes, which are essential in various scientific and industrial applications.

Additional Resources

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Understanding vapor pressure and how it is influenced by different factors is fundamental in fields ranging from chemistry and physics to engineering and environmental science. Vapor pressure essentially indicates the tendency of a liquid to vaporize; it is the pressure exerted by a vapor in equilibrium with its liquid at a given temperature. When substances like salt are dissolved in water, they alter the vapor pressure, leading to a phenomenon known as vapor-pressure lowering. This concept not only explains everyday occurrences, such as why salt is added to boiling water but also underpins critical industrial processes like distillation and refrigeration.

In this article, we will explore the calculation of vapor-pressure lowering, starting with the fundamental principles, moving through the relevant equations, and applying practical examples to illustrate the concept. Our specific focus will be on water at 20°C, with a given vapor pressure of 17.54 Torr, and we will delve into how the addition of a solute influences this vapor pressure.

Understanding Vapor Pressure and Its Significance

What Is Vapor Pressure?

Vapor pressure is a thermodynamic property that reflects how easily a liquid vaporizes at a specific temperature. It’s a measure of the escaping tendency of molecules from the liquid phase into the vapor phase. When a liquid is placed in a closed container, molecules constantly evaporate from the surface, and some molecules condense back into the liquid. The vapor pressure is the pressure exerted by this vapor when the rates of evaporation and condensation are equal, reaching an equilibrium.

Why Does Vapor Pressure Matter?

- Boiling Point Determination: The boiling point of a liquid is the temperature at which its vapor pressure equals the atmospheric pressure. For water at 20°C, the vapor pressure is 17.54 Torr, which is below standard atmospheric pressure (760 Torr), meaning water does not boil at this temperature.
- Industrial Applications: In distillation, vapor pressure differences are exploited to separate mixtures. In refrigeration, controlled vapor pressures enable cooling cycles.
- Environmental Impacts: Vapor pressure influences evaporation rates, humidity, and climate-related phenomena.

Vapor Pressure of Water at 20°C

At 20°C, pure water exhibits a vapor pressure of approximately 17.54 Torr. This value indicates that, at this temperature, water molecules exert a modest pressure due to evaporation. When a non-volatile solute such as salt is added, the vapor pressure decreases—a phenomenon known as vapor-pressure lowering.

The Principles Behind Vapor-Pressure Lowering

Raoult’s Law: The Foundation

The primary theoretical framework for understanding vapor-pressure lowering is Raoult’s Law. It states that the vapor pressure of a solvent in an ideal solution is proportional to the mole fraction of the solvent:

$$ P_{solution} = \chi_{solvent} \times P^{\circ}_{solvent} $$

Where:
- $P_{solution}$ is the vapor pressure of the solvent in the solution.
- $\chi_{solvent}$ is the mole fraction of the solvent.
- $P^{\circ}_{solvent}$ is the vapor pressure of the pure solvent at the same temperature.

Implications of Raoult’s Law

- When a non-volatile solute is added, the mole fraction of the solvent decreases.
- This reduction in mole fraction results in a lower vapor pressure.
- The extent of lowering depends on the amount of solute added and its nature (ideally, non-volatile and non-reactive).

Vapor-Pressure Lowering Equation

The change in vapor pressure, ΔP, can be calculated as:

$$ \Delta P = P^{\circ}_{solvent} - P_{solution} = X_{solute} \times P^{\circ}_{solvent} $$

or more commonly expressed as:

$$ \Delta P = i \times K_{b} \times m $$

for solutions where i is the van 't Hoff factor, K_{b} is the molal boiling point elevation constant, and m is molality.

In dilute solutions, the approximation:

$$ \Delta P = P^{\circ}_{solvent} \times X_{solute} $$

is often sufficient.

Calculating Vapor-Pressure Lowering: Step-by-Step Guide

Step 1: Identify Known Values

Suppose you have a solution of water at 20°C, with the vapor pressure of pure water:

- $P^{\circ} = 17.54\, \text{Torr}$

And you add a certain amount of a non-volatile solute, such as sodium chloride (NaCl). To find the vapor-pressure lowering, you must know:

- The amount of solute added (mass or molar amount).
- The volume of solvent.
- The molecular weight of the solute.
- The total moles of solvent.

Step 2: Calculate the Mole Fraction of Water

The mole fraction of water, X_{water}, is:

$$X_{water} = \frac{n_{water}}{n_{water} + n_{solute}}$$

Where:
- n_{water} is the number of moles of water.
- n_{solute} is the number of moles of solute.

Step 3: Apply Raoult’s Law to Find the New Vapor Pressure

Once X_{water} is known:

$$P_{water} = X_{water} \times P^{\circ}$$

The vapor-pressure lowering:

$$\Delta P = P^{\circ} - P_{water} = P^{\circ} \times (1 - X_{water})$$

This value indicates how much the vapor pressure decreases due to the solute.

Practical Example: Salt Dissolution in Water

Let’s consider a practical scenario: dissolving 10 grams of NaCl into 1 liter of water at 20°C.

Step 1: Calculate Moles of Water

- Molar mass of water M_{water} = 18.015 g/mol
- Mass of water: approximately 1000 g (since 1 liter of water weighs about 1000 g)

$$ n_{water} = \frac{1000\, \text{g}}{18.015\, \text{g/mol}} \approx 55.5\, \text{mol} $$

Step 2: Calculate Moles of NaCl

- Molar mass of NaCl M_{NaCl} = 58.44 g/mol

$$ n_{NaCl} = \frac{10\, \text{g}}{58.44\, \text{g/mol}} \approx 0.171\, \text{mol} $$

Step 3: Calculate Mole Fraction of Water

$$ X_{water} = \frac{n_{water}}{n_{water} + n_{NaCl}} = \frac{55.5}{55.5 + 0.171} \approx \frac{55.5}{55.671} \approx 0.9969 $$

Step 4: Compute Vapor-Pressure Lowering

$$ \Delta P = P^{\circ} \times (1 - X_{water}) = 17.54\, \text{Torr} \times (1 - 0.9969) $$

$$ \Delta P \approx 17.54\, \text{Torr} \times 0.0031 \approx 0.054\, \text{Torr} $$

Result: The vapor pressure of water decreases by approximately 0.054 Torr when 10 grams of NaCl are dissolved in 1 liter of water at 20°C.

Factors Influencing Vapor-Pressure Lowering

While the calculation above provides a straightforward estimate, several factors can influence the actual vapor-pressure lowering:

- Nature of the Solute: Ideal solutions assume non-volatile, non-reactive solutes. Real solutions may deviate due to ion interactions or solute volatility.
- Concentration of Solute: Higher concentrations lead to greater vapor-pressure lowering.
- Temperature: As temperature increases, vapor pressure increases, and the impact of solutes may vary accordingly.
- Solution Non-Ideality: Deviations from Raoult’s Law occur in solutions with strong solute-solvent interactions or in concentrated solutions.

Applications and Implications of Vapor-Pressure Lowering

Understanding vapor-pressure lowering is essential across numerous scientific and industrial domains:

- Food Preservation: Salt and sugar are added to foods to reduce vapor pressure and inhibit microbial growth.
- Chemical Engineering: Precise control of vapor pressures is vital in distillation and solvent recovery.
- Pharmaceuticals: Ensuring stability and controlled release of drugs often involves manipulating vapor pressures.
- Environmental Science: Vapor pressure influences evaporation rates, humidity, and climate models.

In summary, calculating the vapor-pressure lowering involves understanding the molecular interactions within solutions, applying fundamental principles like Raoult's Law, and performing precise mole calculations. While the simplified example with NaCl illustrates the concept, real-world applications may require more complex considerations, including non-ideality and temperature effects.

Conclusion

The vapor pressure of water at 20°C is a well-defined physical property, measuring 17.54 Torr. When a

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