In A Container Of Negligible Mass 30g Of Steam At 100C Is Added To 200g Of Water That Has A Temperature

In A Container Of Negligible Mass 30g Of Steam At 100°C Is Added To 200g Of Water That Has A Temperature of a certain value, the process involves complex thermodynamic interactions that determine the final equilibrium temperature of the system. This scenario is a classic example in physics and engineering, illustrating principles of heat transfer, phase change, and energy conservation. Understanding such processes is essential in various applications, including heating systems, industrial processes, and environmental science. In this article, we explore the detailed mechanics behind adding steam at 100°C to water, analyze the energy exchanges involved, and derive the final temperature of the mixture.

Understanding the Scenario: Key Parameters and Assumptions

Before delving into calculations, it is crucial to define the parameters and assumptions involved in this problem:

Parameters

- Mass of steam, m_{steam} = 30 grams (0.03 kg)
- Temperature of steam, T_{steam} = 100°C
- Mass of water, m_{water} = 200 grams (0.2 kg)
- Initial temperature of water, $T_{initial}$ = unknown (variable)

Assumptions

1. The container has negligible mass and does not affect heat transfer calculations.
2. The steam is at 100°C and fully condenses upon contact with water at or below 100°C.

3. Latent heat of vaporization of water, L_v = 2260 kJ/kg.
4. Specific heat capacity of liquid water, c_{water} = 4184 J/(kg·°C).
5. Heat losses to the environment are negligible.
6. All processes occur quasi-statically, allowing us to apply thermodynamic principles straightforwardly.

Fundamental Concepts in Heat Transfer and Phase Change

Understanding the problem requires familiarity with several key thermodynamic concepts:

Heat of Vaporization

The energy required to convert water from liquid to vapor at boiling point without changing temperature:

- L_v = 2260 kJ/kg
- This energy is released when vapor condenses back into liquid.

Specific Heat Capacity

The amount of heat needed to raise the temperature of a unit mass of a substance by 1°C:

- c_{water} = 4184 J/(kg·°C)

Energy Conservation Principle

In an isolated system, the total energy remains constant:

- Heat lost by steam during condensation and cooling equals heat gained by water.

Step-by-Step Analysis of the Process

The process involves several stages:
1. Condensation of steam at 100°C.
2. Cooling of condensed water from 100°C to the final equilibrium temperature.
3. Heating of the initial water from its initial temperature to the final temperature.
4. Equilibrium is achieved when the net heat exchange balances out.

Let’s analyze each step in detail.

Step 1: Condensation of Steam

When 30g of steam at 100°C condenses:
- Energy released = mass of steam × latent heat
- Qcondensation = msteam × Lv

Calculations:
- msteam = 0.03 kg
- Qcondensation = 0.03 kg × 2260 kJ/kg = 67.8 kJ = 67,800 J

This energy is released into the system, heating the water and the condensed liquid.

Step 2: Cooling of Condensed Water

The condensed water initially at 100°C cools down to the final equilibrium temperature Tf:
- Heat lost = msteam × cwater × (100°C – Tf)
- Qcooling = 0.03 kg × 4184 J/(kg·°C) × (100 – Tf)

Step 3: Heating of Initial Water

The initial water at Tinitial gains heat to reach Tf:
- Heat gained = mwater × cwater × (Tf – Tinitial)
- Qheating = 0.2 kg × 4184 J/(kg·°C) × (Tf – Tinitial)

Step 4: Final Energy Balance

Since the system is isolated:
- Total heat released by condensation and cooling = heat gained by initial water

Mathematically:

Qcondensation + Qcooling = Qheating

Expressed as:
$67{,}800\ J + 0.03\ kg \times 4184\ J/(kg\cdot°C) \times (100 - T_f) = 0.2\ kg \times 4184\ J/(kg\cdot°C) \times (T_f - T_{initial})$

Simplify:
$67{,}800 + 0.03 \times 4184 \times (100 - T_f) = 0.2 \times 4184 \times (T_f - T_{initial})$

Calculations:
- $0.03 \times 4184 \approx 125.52\ J/°C$
- $0.2 \times 4184 \approx 836.8\ J/°C$

Plugging in:
$67{,}800 + 125.52 \times (100 - T_f) = 836.8 \times (T_f - T_{initial})$

Rearranged:
$67{,}800 + 12{,}552 - 125.52\ T_f = 836.8\ T_f - 836.8\ T_{initial}$

Combine constants:
$80{,}352 - 125.52\ T_f = 836.8\ T_f - 836.8\ T_{initial}$

Bring all Tf terms to one side:
$80{,}352 = 836.8\ T_f + 125.52\ T_f - 836.8\ T_{initial}$

Combine Tf terms:
$80{,}352 = (836.8 + 125.52)\ T_f - 836.8\ T_{initial}$

Sum:
$80{,}352 = 962.32\ T_f - 836.8\ T_{initial}$

Finally, solve for Tf:
$T_f = [80{,}352 + 836.8\ T_{initial}] / 962.32$

This equation relates the final temperature to the initial water temperature.

Analyzing Specific Cases

The final equilibrium temperature depends heavily on the initial water temperature Tinitial. Let's examine various scenarios:

Case 1: Initial Water Temperature at 25°C

- Tinitial = 25°C
- Tf = [80,352 + 836.8 × 25] / 962.32
- Calculate numerator:
80,352 + 20,920 = 101,272
- Final temperature:
Tf ≈ 101,272 / 962.32 ≈ 105.2°C

Since this exceeds 100°C, in reality, the water cannot be heated above boiling point without additional energy; thus, the temperature would stabilize at 100°C, and residual energy would cause boiling or vaporization. This highlights the importance of phase change considerations.

Case 2: Initial Water Temperature at 80°C

- Tinitial = 80°C
- Tf = (80,352 + 836.8 × 80) / 962.32
- Numerator:
80,352 + 66,944 = 147,296
- Tf ≈ 147,296 / 962.32 ≈ 153°C

Frequently Asked Questions

What happens when 30g of steam at 100°C is added to 200g of water at a lower temperature?

The steam condenses into water, releasing latent heat, which raises the temperature of the existing water, potentially leading to a new equilibrium temperature.

How do you calculate the final temperature after adding steam to water?

Use the principle of conservation of energy, equating the heat lost by condensing steam to the heat gained by the water, considering latent heat of vaporization and specific heat capacities.

What is the latent heat of vaporization of water at 100°C?

The latent heat of vaporization of water at 100°C is approximately 2260 kJ/kg.

If the initial water temperature is below 100°C, how does the addition of steam affect the temperature?

The condensation of steam releases heat, which raises the water temperature until a new equilibrium is reached, possibly reaching 100°C or higher if enough heat is transferred.

Can the final temperature of water exceed 100°C in this scenario?

No, unless the system is under pressure, water cannot exceed 100°C at atmospheric pressure; the temperature will approach 100°C and stabilize as phase changes occur.

How much water will be formed after the steam condenses?

All 30g of steam will condense into water, adding to the existing 200g of water, resulting in approximately 230g of water at the new temperature.

What is the significance of the negligible mass assumption for the steam?

It allows simplifying calculations by ignoring the mass of the container and focusing solely on heat exchanges between the steam and water.

How does the specific heat capacity of water influence the temperature change in this process?

The specific heat capacity determines how much the temperature of water increases for a given amount of heat absorbed; higher heat capacity means smaller temperature rise for the same heat input.

What are common real-world applications of this process?

This process is relevant in steam heating systems, calorimetry experiments, and understanding phase change heat transfer in thermodynamics.

What assumptions are typically made in calculations involving steam condensation into water?

Assumptions often include negligible mass of the container, no heat loss to surroundings, and that all the steam condenses completely at 100°C.

Additional Resources

In a container of negligible mass, 30 grams of steam at 100°C is added to 200 grams of water at an initial temperature, leading to a complex interplay of thermal energy transfer, phase change, and temperature equilibrium. This scenario is not only a classical problem in thermodynamics but also provides insights into the principles governing heat transfer, latent heat, and the behavior of water and steam under different conditions. Understanding the outcome necessitates a detailed analysis of the energy exchanges involved, the state of the system before and after mixing, and the physical laws that describe such processes.

Introduction: The Significance of the Scenario

The described situation presents a fundamental thermodynamic problem that appears simple on the surface—adding steam to water—but reveals rich physical phenomena upon closer inspection. It epitomizes the interactions between different phases of water, namely liquid and vapor, and demonstrates how energy transfer leads to phase changes, temperature adjustments, or equilibrium states.

This scenario is particularly significant because it embodies core concepts such as:

- The conservation of energy
- Latent heat of vaporization
- Specific heat capacity
- Equilibrium conditions between phases
- The importance of initial conditions in thermodynamic systems

In real-world applications, understanding such processes is crucial in fields ranging from climate science and meteorology to industrial processes like distillation, sterilization, and power plant operations.

System Description and Assumptions

To analyze this problem accurately, it is essential to define the assumptions and parameters for the system:

- Mass of water (liquid): 200 g (0.2 kg)
- Initial temperature of water: T_1 (unknown, but often assumed for analysis)
- Mass of steam: 30 g (0.03 kg)
- Temperature of steam before addition: 100°C

- Mass of the container: negligible (no heat capacity)
- Heat capacity of the container: negligible
- Surroundings: assumed to be an infinite thermal reservoir at a constant temperature, or isolated for the scope of analysis
- Initial conditions: The water is initially at some temperature T_1 less than, equal to, or greater than 100°C (but in typical scenarios, $T_1 < 100°C$)

The specific heat capacities and latent heats involved are fundamental to the analysis:

- Specific heat capacity of water (liquid): c_p = 4186 J/(kg·K)
- Latent heat of vaporization of water at 100°C: L_v = 2257 kJ/kg

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Physical Principles Underpinning the Process

Before delving into calculations, a clear understanding of the physical principles is necessary:

1. Heat Transfer and Equilibrium

When the steam is introduced into the water, heat exchange occurs:

- The steam can condense, releasing latent heat.
- The liquid water can absorb heat, increasing its temperature.
- If the combined energy exchange results in the entire steam condensing, the system reaches a new equilibrium temperature, possibly close to or at boiling point, depending on initial conditions.

2. Phase Changes: Condensation and Heating

- Condensation of Steam: Conversion from vapor to liquid releases latent heat of vaporization.
- Heating of Water: Both the initial water and condensed water can increase in temperature depending on the energy received.

3. Conservation of Energy

The total energy before and after mixing remains constant, assuming no heat loss to surroundings:

\[\text{Heat lost} = \text{Heat gained} \]

4. Possible Outcomes

Depending on initial conditions and energy exchanges, several scenarios are possible:

- Complete condensation of the steam, raising the water temperature but not boiling it.
- Partial condensation, with some steam remaining vapor.
- No condensation if the water's temperature is too low, preventing the steam from condensing.

Step-by-Step Analytical Approach

1. Establishing Initial Conditions

For simplicity, assume the initial temperature of the water is T_1, which is less than 100°C (e.g., room temperature, say 25°C). The steam is at 100°C and can condense upon contact with water at or below 100°C.

2. Calculating Energy Exchanges

- Energy released by condensing all 30 g of steam:

$$
Q_{condensation} = m_{steam} \times L_v = 0.03 \, \text{kg} \times 2257 \times 10^3 \, \text{J/kg} = 67,710 \, \text{J}
$$

- Energy required to heat the initial water from T_1 to 100°C (if $T_1 < 100$°C):

$$
Q_{heat\,water} = m_{water} \times c_p \times (100 - T_1)
$$

Where T_1 is in °C.

- Energy to heat the condensed water (from vapor to 100°C):

If the steam condenses, it becomes liquid at 100°C, so no additional heating is needed for the phase change itself, but if the condensed water is initially at 100°C, no further heating is necessary.

3. Conditions for Complete Condensation

Complete condensation occurs if:

$$
Q_{condensation} \geq Q_{heat\,water}
$$

This implies the energy released by the condensation is sufficient to raise the initial water's temperature to 100°C, and potentially more.

Calculations and Outcomes

Scenario A: Water at Room Temperature (~25°C)

- Calculate energy needed to raise water from 25°C to 100°C:

$$
Q_{water\,rise} = 0.2\, \text{kg} \times 4186\, \text{J/(kg·K)} \times (100 - 25) = 0.2 \times 4186 \times 75 = 62,790\, \text{J}
$$

- Compare with energy released by condensing all steam:

$$
Q_{condensation} = 67,710\, \text{J}
$$

Since 67,710 J > 62,790 J, the steam releases enough energy to:

- Condense fully
- Heat the initial water from 25°C to 100°C
- The excess energy will be available for further heating or vaporization.

- Remaining energy after heating water to 100°C:

$$
Q_{remaining} = 67,710 - 62,790 = 4,920\, \text{J}
$$

- Additional heating of the now 0.23 kg of water (initial + condensed):

Total mass after condensation: 0.2 kg + 0.03 kg = 0.23 kg

- Could the system reach boiling point?

Given the excess energy, the water may be heated beyond 100°C if the system is open or if pressure increases, but under typical conditions, the temperature stabilizes at 100°C, with excess energy contributing to vaporization if the container allows.

Final Equilibrium State:

- All 30 g of steam condenses into water at 100°C.
- The initial water heats up from 25°C to 100°C.
- The total water mass becomes 230 g at approximately 100°C.

Real-World Considerations and Limitations

While the idealized calculations suggest complete condensation and temperature rise to boiling point, real systems involve complexities:

- Heat Losses: In practice, some heat might be lost to surroundings, reducing the final temperature.
- Pressure Effects: If the container is sealed, pressure increases as steam condenses and heats, potentially raising boiling point beyond 100°C.
- Non-idealities: Impurities, container material, and initial temperature variations all influence the outcome.

Implications and Applications

Understanding this process is pivotal in multiple domains:

- Industrial Processes: In distillation, where vapor-liquid interactions are central.
- Meteorology: Cloud formation involves water vapor condensing onto particulates.
- Power Generation: Condensation of steam in turbines and condensers relies on thermodynamic principles similar to this scenario.
- Climate Science: The energy exchange during phase changes influences weather patterns and energy budgets.

Concluding Remarks

The scenario of adding a negligible mass of steam at 100°C to water at an initial temperature exemplifies the interconnectedness of heat transfer, phase change, and thermodynamic equilibrium. Under ideal conditions and initial assumptions, the process results in full condensation of the steam, heating the water to 100°C, and increasing the total water mass at boiling temperature. These fundamental principles underscore the importance of latent heat and specific heat capacities in thermal systems.

In practical terms, accurately predicting outcomes requires considering additional factors such as container constraints, heat losses, and pressure variations. Nonetheless, the core concepts remain consistent, providing a foundation for understanding more complex thermal phenomena encountered in engineering, meteorology, and environmental sciences.

The insights gained from such analyses not only deepen our understanding of water's behavior under thermal manipulations but also exemplify the elegance of thermodynamics in explaining everyday and industrial processes alike.

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