A Well-insulated Rigid Tank Having A Volume Of 10ft^3 Containssaturated Water Vapor At 212 Degrees F.

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This scenario presents an intriguing thermodynamic problem involving the behavior of saturated water vapor within a confined, insulated environment. Understanding the properties and changes that occur in such a system is fundamental to disciplines like mechanical engineering, thermodynamics, and process engineering. In this article, we will explore the physical principles governing the behavior of saturated water vapor in a rigid, well-insulated tank, analyze the thermodynamic state, and discuss relevant calculations and implications.

Understanding the System: Key Concepts and Definitions

1. Rigid Tank and Its Significance

A rigid tank is one whose volume remains constant during the process. In our case, the volume is fixed at 10 cubic feet (ft^3). This constraint simplifies analysis because it eliminates the need to consider volume changes, focusing instead on pressure, temperature, and phase behavior.

2. Well-insulated Environment

The tank's insulation implies negligible heat transfer with the surroundings. Consequently, the process within the tank is adiabatic, meaning the total internal energy and other properties change only due to internal phenomena like phase change or pressure variations, without heat exchange.

3. Saturated Water Vapor at 212°F

The initial state involves saturated water vapor at 212°F (roughly 100°C). Saturation indicates that the vapor exists in equilibrium with liquid water at this temperature, with the vapor pressure corresponding to saturation pressure at that temperature.

Thermodynamic Properties of Water at 212°F

1. Saturation Pressure at 212°F

At 212°F (100°C), the saturation pressure of water is approximately 14.7 psia (pounds per square inch absolute). This is the standard atmospheric boiling point for water, making the scenario familiar in everyday contexts such as boiling water.

2. Specific Volume of Saturated Water Vapor

The specific volume (volume per unit mass) of saturated water vapor at 212°F is approximately 0.4624 ft^3/lb. This property is essential for calculating the amount of vapor present in the tank.

3. Enthalpy and Internal Energy

At saturation conditions, water vapor's enthalpy (h) and internal energy (u) are critical for understanding energy changes. Typical values at 212°F are:

- Enthalpy of vaporization (h_{fg}): approximately 970 Btu/lb
- Specific enthalpy of saturated vapor (h_g): roughly 1150 Btu/lb

These values will inform calculations related to energy content and phase behavior.

Initial State Analysis

1. Calculating the Mass of Water Vapor in the Tank

Given the volume of the tank (V) and the specific volume (v_g) of saturated vapor, the mass (m) can be found as:

$$ m = \frac{V}{v_g} $$

Where:
- $V = 10\ ft^3$
- $v_g \approx 0.4624\ ft^3/lb$

Thus:
$$ m = \frac{10}{0.4624} \approx 21.63\, \text{lb} $$

This indicates approximately 21.63 pounds of water vapor are initially contained within the tank.

2. Internal Energy and Enthalpy

Using the specific enthalpy (h_g), the total internal energy (U) and enthalpy (H) are:

- $U = m \times u_g$
- $H = m \times h_g$

Assuming u_g (internal energy per lb) is around 1150 Btu/lb at saturation, the total energy content can be estimated.

Behavior of the System: Thermodynamic Considerations

1. No Heat Transfer Due to Insulation

Since the tank is well-insulated, no heat enters or leaves the system. Any internal phase change or pressure change occurs solely due to internal energy redistribution.

2. Phase Stability and Potential Changes

Because the vapor is initially saturated at 212°F, the system is at equilibrium. If the vapor cools or heats (without heat exchange), phase changes could occur. However, since the environment is insulated and static, the initial state remains stable unless an internal process such as condensation or evaporation occurs due to internal energy changes.

3. Pressure-Temperature Relationship in a Rigid Tank

In a rigid, insulated tank, the pressure and temperature are directly related through the saturation properties of water. Since the water vapor is initially saturated at 212°F, the pressure inside the tank is approximately 14.7 psia.

Potential Scenarios and Analyses

1. Isothermal Process (Constant Temperature)

If the system remains at constant temperature (say, due to initial equilibrium), the pressure stays at saturation pressure corresponding to 212°F. The internal energy remains largely unchanged unless phase change occurs, which is stabilized at equilibrium.

2. Heating or Cooling Without Volume Change

In reality, if the vapor's internal energy changes (due to internal chemical reactions or other phenomena), the temperature could change, leading to superheated vapor or condensation. However, since the tank is insulated and volume fixed, phase changes depend solely on internal energy shifts.

3. Condensation or Evaporation within the Tank

If internal energy decreases, vapor may condense into liquid water, reducing the vapor mass and pressure. Conversely, if energy increases, additional vapor could be generated, increasing pressure.

Implications and Practical Applications

1. Safety Considerations

Understanding the pressure and phase behavior in such a tank is vital for safety. Over-pressurization could lead to rupture, especially if internal energy increases unexpectedly.

2. Industrial Applications

This setup models many real-world systems, such as pressure vessels, boilers, or containment tanks in chemical processing, where maintaining specific states of water or steam is critical.

3. Thermodynamic Calculations for Design and Control

Engineers can utilize these principles to design systems that manage phase changes effectively, ensuring safety, efficiency, and reliability.

Advanced Topics and Calculations

1. Using Steam Tables and Mollier Diagrams

To analyze such systems accurately, engineers refer to steam tables or Mollier diagrams, which provide detailed property data at various temperatures and pressures.

2. Energy Balance Equations

Applying the first law of thermodynamics for an isolated system yields:

$$ \Delta U = 0 $$

since no heat transfer or work occurs, any internal phase change must conserve the total energy.

3. Estimating Changes in the System

For example, if an internal process causes the vapor to condense, the mass of vapor reduces, and the pressure drops accordingly. Calculations involve:

- Determining new vapor and liquid masses
- Recalculating pressure using saturation properties
- Assessing the energy release or absorption during phase change

Conclusion

A well-insulated, rigid tank containing saturated water vapor at 212°F exemplifies fundamental thermodynamic principles. By understanding the initial conditions, property data, and the implications of insulation and volume constraints, engineers can predict the system's behavior under various scenarios. Whether analyzing safety, designing pressure vessels, or controlling phase changes in industrial processes, mastering these concepts ensures efficient and safe operation. The interplay of pressure, temperature, internal energy, and phase stability underscores the importance of thermodynamics in real-world applications, reinforcing the critical role of precise calculations and property data in engineering practice.

Frequently Asked Questions

What is the state of water vapor at 212°F in a well-insulated rigid tank of 10 ft^3?

The water vapor is saturated at 212°F, meaning it exists at its boiling point with both liquid and vapor phases in equilibrium inside the rigid tank.

What is the pressure of saturated water vapor at 212°F?

The saturation pressure of water vapor at 212°F (100°C) is approximately 1 atm or 101.3 kPa.

How can the specific volume of saturated water vapor at 212°F be determined?

It can be obtained from standard steam tables, which typically list the specific volume as about 0.0231 ft^3/lb for saturated vapor at 212°F.

What is the mass of water vapor in the tank at saturation and 212°F?

Using the specific volume, the mass can be calculated as mass = tank volume / specific volume. For 10 ft^3 and specific volume 0.0231 ft^3/lb, mass ≈ 432.9 lb.

Is the water vapor in the tank at a higher or lower energy state compared to subcooled water at the same temperature?

The saturated vapor at 212°F has higher internal energy and enthalpy compared to subcooled (liquid) water at the same temperature.

What assumptions are typically made when analyzing a well-insulated rigid tank containing saturated water vapor?

Assumptions include no heat transfer (adiabatic conditions), constant volume, and the water vapor being at saturation conditions at 212°F.

How does the volume of the tank relate to the phase of water inside at saturation conditions?

At saturation, the volume is directly related to the mass of vapor and its specific volume; since the tank is rigid and well-insulated, the volume remains constant during any process.

What would happen if heat were added to this well-insulated tank at constant volume?

If heat were added, the vapor would become superheated, increasing temperature and pressure beyond saturation at 212°F, assuming the tank can withstand the pressure.

How can the internal energy of the saturated vapor at 212°F be estimated?

Using steam tables, the internal energy (u) per unit mass at 212°F is approximately 1177.2 Btu/lb for saturated vapor.

What safety considerations are important when handling a rigid tank containing saturated water vapor at 212°F?

Since the vapor is at saturation pressure, the tank must be designed to withstand approximately 1 atm, and any heating or pressure changes should be carefully controlled to prevent rupture or accidents.

Additional Resources

A Well-insulated Rigid Tank Having a Volume of 10 ft³ Containing Saturated Water Vapor at 212°F: An In-Depth Analysis

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Introduction

A well-insulated rigid tank containing saturated water vapor at 212°F presents a fascinating case study in thermodynamics, fluid mechanics, and energy conservation. Such systems are vital in various industrial applications, including steam generation, thermal storage, and pressure regulation. This article explores the intricacies of this setup, analyzing the physical conditions within the tank, energy interactions, phase behavior, and potential practical implications. By examining this scenario thoroughly, engineers and scientists can better understand the fundamental principles governing phase change, energy transfer, and system stability under specific thermal conditions.

Physical Characteristics and Initial Conditions

Tank Specifications and Physical Setup

The tank in question is rigid and well-insulated, meaning:

- Rigid: The tank's volume remains constant at 10 ft³, with no deformation or volume change during operation.
- Well-insulated: Minimal heat exchange occurs with the environment, implying an adiabatic condition.

- Volume: Fixed at 10 ft^3, which influences pressure and temperature relationships within the contained vapor.

The initial condition specifies saturated water vapor at 212°F. This temperature is notably significant because:

- 212°F corresponds to 100°C, the boiling point of water at standard atmospheric pressure.
- The saturation state indicates equilibrium between the vapor and liquid phases, with vapor pressure matching the atmospheric pressure at this temperature.

Physical State of Water in the Tank

Given the saturation condition:

- The vapor pressure of water at 212°F is approximately 14.7 psia (pounds per square inch absolute), equivalent to standard atmospheric pressure.
- The water vapor occupies the entire volume in the saturated state, with the possibility of some liquid phase if the conditions allow.

The critical question is whether the tank contains only vapor or a mixture of vapor and liquid. Since the description specifies saturated water vapor, it's typically understood that the tank contains vapor at equilibrium with a small amount of liquid phase, or it is entirely vapor at the saturation point.

Thermodynamic Analysis of the System

Pressure and Temperature Relationship

In saturated conditions, the pressure and temperature are directly related via the saturation curve:

- At 212°F, the saturation pressure for water is approximately 14.7 psia.
- The thermodynamic state can be characterized using standard steam tables, which provide properties like specific volume, enthalpy, and entropy at saturation.

Key parameters at saturation for water at 212°F:

Property	Value
Saturation Temperature (T_sat)	212°F (100°C)

Saturation Pressure (P_{sat})	14.7 psia
Specific Volume of Saturated Vapor (v_g)	approximately 0.4624 ft³/lb
Specific Volume of Saturated Liquid (v_f)	approximately 0.01604 ft³/lb

Since the system contains saturated vapor in a 10 ft³ volume, the mass of vapor can be estimated:

$$
m = \frac{V}{v_g} = \frac{10\, \text{ft}^3}{0.4624\, \text{ft}^3/\text{lb}} \approx 21.64\, \text{lb}
$$

This indicates the tank contains approximately 21.64 pounds of water vapor at saturation conditions.

Energy Considerations and Internal State

Internal Energy and Enthalpy of Saturated Water Vapor

Understanding the energy content requires examining the specific internal energy (u_g) and enthalpy (h_g) of saturated vapor at 212°F.

From steam tables:

Property	Value
Specific Enthalpy of vapor (h_g)	approximately 1180.4 Btu/lb
Specific Internal Energy (u_g)	approximately 1050 Btu/lb

Using these, the total internal energy (U) and enthalpy (H) within the tank are:

$$
U = m \times u_g \approx 21.64\, \text{lb} \times 1050\, \text{Btu/lb} \approx 22,722\, \text{Btu}
$$

$$
H = m \times h_g \approx 21.64\, \text{lb} \times 1180.4\, \text{Btu/lb} \approx 25,565\, \text{Btu}
$$

Because the tank is adiabatic, the total energy U remains constant unless some phase change occurs due to external influences.

Implications of Insulation and Rigid Structure

The key features influencing the system's thermodynamics are:

- Adiabatic condition: No heat exchange with surroundings.
- Rigid tank: No volume change, so pressure and temperature can only change due to internal energy variations or phase changes.
- Saturation state maintenance: Under ideal conditions, the vapor remains at saturation; any energy input would tend to cause phase change or temperature increase, but since the tank is insulated, the system’s energy state is conserved unless phase change or other processes occur.

Potential Dynamic Scenarios and System Behavior

Scenario 1: Isothermal and Saturated Condition Maintained

If the tank remains perfectly insulated and no external energy is added or removed, the initial conditions are stable:

- The vapor remains saturated at 212°F.
- The pressure stays constant at approximately 14.7 psia.
- No phase change occurs, and the internal energy remains steady.

This ideal state is theoretically stable but practically sensitive to minor perturbations, such as temperature fluctuations or pressure variations.

Scenario 2: Heating or Cooling Within the Tank

- Adding heat: Because the tank is well-insulated, any heat added would increase the internal energy, potentially causing some of the saturated vapor to condense into liquid, or raising the temperature slightly above saturation, leading to superheated vapor.
- Removing heat: Would decrease internal energy, potentially causing some vapor to condense into liquid, leading to a mixture of phases or complete condensation if enough heat is extracted.

In real systems, these processes might lead to phase changes, pressure variations, and temperature shifts, which must be managed carefully in practical applications.

Scenario 3: Pressure and Temperature Deviations

Any disturbance altering the pressure or temperature (e.g., external shocks or imperfections in insulation) could:

- Shift the system away from saturation.
- Induce condensation or boiling.
- Alter the internal energy distribution.

These phenomena highlight the importance of maintaining ideal conditions or designing for controlled phase changes in engineering systems.

Practical Applications and Significance

Understanding such a system's behavior is essential across multiple disciplines:

- Steam generation: Ensuring consistent pressure and temperature within boilers and tanks.
- Thermal energy storage: Using saturated vapor for storing and releasing energy.
- Pressure regulation: Designing safety and control systems that account for phase change behavior under insulated conditions.
- Industrial processes: Managing phase equilibrium and energy transfer in chemical, power, and manufacturing plants.

By analyzing the thermodynamics of a saturated vapor in a rigid, insulated tank, engineers can optimize system design, ensure safety, and improve efficiency.

Conclusion

The examination of a well-insulated, rigid tank of 10 ft^3 containing saturated water vapor at 212°F reveals a complex interplay of thermodynamic principles. From the specific properties of water vapor at saturation to the implications of perfect insulation and rigidity, this scenario underscores the importance of understanding phase behavior, energy conservation, and system stability. Such insights are crucial for designing reliable pressure vessels, thermal storage systems, and process equipment. Moreover, recognizing the delicate balance maintained at saturation conditions helps engineers develop strategies for safe operation and energy management in various industrial contexts, highlighting the enduring relevance of classical thermodynamics in modern engineering solutions.

This comprehensive review underscores the importance of precise thermodynamic analysis in understanding and optimizing systems involving saturated water vapor in insulated, rigid containers, illustrating their vital roles across industries and scientific research.

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