Thermodynamics - HW2

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Question 1

Describe the concept of a state in thermodynamics. How do state functions differ from path functions, and why are properties such as pressure and temperature considered state functions?

Concept of a State in Thermodynamics

In thermodynamics, the **state** of a system is defined by a set of properties that describe its condition at a particular instant. These properties include temperature, pressure, volume, and internal energy. The state of a system provides complete information about the system's equilibrium condition and determines all other properties through established relations.

A system is said to undergo a **process** when it transitions from one state to another due to changes in its properties. If a system returns to its original state after undergoing a series of changes, it is said to have completed a **thermodynamic cycle**.

State Functions vs. Path Functions

Thermodynamic properties are classified into two categories: **state functions** and **path functions**.

- State Functions: These are properties that depend only on the initial and final states of a system and not on the path taken to reach the final state. Examples include temperature, pressure, volume, and internal energy. For instance, the altitude of a mountain is independent of the path taken to reach the top.

- Path Functions: These depend on the specific path taken between two states. Examples include work and heat. Unlike state functions, path functions are influenced by how a process occurs rather than just the initial and final conditions. For example, the total distance traveled in a journey depends on the route taken.

Why Pressure and Temperature are State Functions

Pressure and temperature are considered state functions because their values at any given state are unique and do not depend on how the system reached that state. These properties are intrinsic to the system's equilibrium condition and can be determined solely by knowing the system's state, irrespective of the history of changes it underwent.

For example:

- A gas in a sealed container at a specific temperature and pressure will always have those properties defined for that state, regardless of how it was heated or compressed.

- The pressure inside a balloon is determined by the gas volume and temperature, not by the way the gas was added or expanded.

Summary

The concept of state in thermodynamics is fundamental for analyzing systems and predicting their behavior. State functions like temperature and pressure are independent of the process path, making them reliable for defining equilibrium conditions. In contrast, path functions depend on the process history and are crucial for understanding energy transfer mechanisms like heat and work.

Question 2

Define steady state as applied to a thermodynamic system. Give an example of a real-world system that operates under steady-state conditions and explain what makes it steady state.

Definition of Steady State in Thermodynamics

In thermodynamics, a system is said to be in a **steady state** if its properties do not change with time. This means that variables such as temperature, pressure, mass flow rate, and energy remain constant at every point within the system over time, even though energy and mass may be flowing through the system.

Mathematically, for a steady-state system:

$$\frac{dX}{dt} = 0 \tag{1}$$

where X represents any thermodynamic property such as internal energy, pressure, or temperature.

A steady-state condition is commonly assumed in engineering analyses because it simplifies calculations and allows for predictable system behavior.

Real-World Example: Steam Power Plant

A practical example of a steady-state thermodynamic system is a **steam power plant**. In such a plant:

- Water enters the boiler, where it is heated to produce steam.
- The steam expands through a turbine to generate electricity.
- The steam is then condensed back into water in a condenser.
- The water is pumped back to the boiler to complete the cycle.

This system operates under steady-state conditions because the mass and energy flow rates remain constant over time. Each component—boiler, turbine, condenser, and pump—operates in a continuous manner, ensuring that the system's properties do not change with time.

Conclusion

A steady-state system maintains constant thermodynamic properties over time, making analysis more manageable and predictable. Steam power plants, refrigeration systems, and fluid pipelines are examples of real-world systems that rely on steady-state operation for efficiency and reliability.

Question 3

What is thermal equilibrium? Discuss how it is possible to measure temperature by bringing two systems into thermal equilibrium with a third system.

Definition of Thermal Equilibrium

Thermal equilibrium is a condition in which two or more systems in thermal contact no longer exchange heat, meaning they have reached the same temperature. When thermal equilibrium is achieved, the temperature of all interacting systems remains constant over time.

In thermodynamics, thermal equilibrium is a crucial aspect of the broader concept of equilibrium, which also includes mechanical, phase, and chemical equilibrium.

Measurement of Temperature Using Thermal Equilibrium

The principle of thermal equilibrium is fundamental in temperature measurement and is governed by the **Zeroth Law of Thermodynamics**, which states:

> "If two systems are each in thermal equilibrium with a third system, then they are in thermal equilibrium with each other."

This principle allows the use of thermometers to measure temperature effectively. The process works as follows:

- A thermometer (third system) is brought into contact with a system whose temperature is to be measured.
- Heat exchange occurs between the thermometer and the system until thermal equilibrium is reached.
- Once equilibrium is established, the thermometer reading corresponds to the temperature of the system.

For example, when a mercury thermometer is placed in hot water, the mercury expands until its temperature matches that of the water. The final height of the mercury column provides a direct measure of the water's temperature.

Summary

Thermal equilibrium is a fundamental concept in thermodynamics that allows for accurate temperature measurement. The Zeroth Law of Thermodynamics enables the use of thermometers by ensuring that when a thermometer reaches equilibrium with a system, it accurately reflects the system's temperature. This principle is applied in various scientific and industrial temperature measurement techniques.

Question 4

Compare and contrast open, closed, and isolated systems in thermodynamics. Provide an example of each type of system from everyday life or industrial processes, explaining why each example fits its respective category.

Comparison of Open, Closed, and Isolated Systems

In thermodynamics, systems are classified based on their interactions with the surroundings in terms of mass and energy exchange:

- **Open System:** A system that allows both mass and energy to cross its boundaries.
- **Closed System:** A system that allows energy exchange but not mass transfer.
- **Isolated System:** A system that does not exchange either mass or energy with its surroundings.

System Type	Mass Exchange	Energy Exchange	Example
Open System	Yes	Yes	Boiling pot of water without a lid
Closed System	No	Yes	A sealed pressure cooker
Isolated System	No	No	A well-insulated thermos bottle

Table 1: Comparison of Open, Closed, and Isolated Systems

Examples of Each System

Open System: Boiling Pot of Water Without a Lid

A pot of boiling water on a stove without a lid is an open system because:

- Water vapor (mass) escapes into the surroundings.

- Heat (energy) is transferred from the stove to the pot and then to the water.

Closed System: Sealed Pressure Cooker

A pressure cooker with a sealed lid represents a closed system because:

- No mass can enter or leave the system, as the lid prevents vapor from escaping.

- Energy in the form of heat is transferred from the stove to the contents inside.

Isolated System: Well-Insulated Thermos Bottle

A thermos bottle with a tight lid is an isolated system because:

- It prevents the exchange of mass (no liquid or gas escapes).

- It minimizes heat transfer, keeping the contents hot or cold for an extended period.

Summary

Understanding open, closed, and isolated systems is essential in thermodynamics as it helps analyze energy and mass transfer. These concepts apply to everyday and industrial systems, influencing the efficiency of thermal processes and energy conservation.

Question 5

Explain how a pure substance can exist in different phases (solid, liquid, gas) and what phase equilibrium means. Use the concept of the triple point to illustrate your explanation.

Phases of a Pure Substance

A **pure substance** is a material with a uniform and definite chemical composition. It can exist in three primary phases:

- **Solid:** Molecules are closely packed in a fixed structure with limited movement.
- **Liquid:** Molecules are less tightly packed, allowing fluid motion while maintaining cohesion.
- **Gas:** Molecules are widely spaced and move freely, filling any available volume.

The transition between these phases occurs due to changes in temperature and pressure, such as melting, freezing, vaporization, condensation, and sublimation.

Phase Equilibrium

Phase equilibrium refers to a condition where multiple phases of a pure substance coexist at stable proportions without undergoing net phase change. For example:

- **Liquid-Vapor Equilibrium:** In a sealed container, water and its vapor reach equilibrium when the rate of evaporation equals the rate of condensation.
- **Solid-Liquid Equilibrium:** Ice and water maintain equilibrium at 0°C under standard atmospheric pressure.

Triple Point Concept

The **triple point** of a substance is a unique combination of temperature and pressure at which all three phases (solid, liquid, and gas) coexist in equilibrium. This point is significant because:

- It represents a fundamental thermodynamic state.
- It is used to define absolute temperature scales, such as the Kelvin scale (triple point of water: 273.16 K at 0.611 kPa).
- It serves as a reference for calibrating thermodynamic instruments.

Summary

A pure substance can transition between solid, liquid, and gas phases depending on pressure and temperature. Phase equilibrium ensures stable coexistence of different phases, and the triple point provides a critical reference where all three phases exist simultaneously, offering valuable insights into thermodynamic behavior.

Question 6

Calculate the molarity of a solution prepared by dissolving 14.2 grams of Sodium Sulfate (Na_2SO_4) in enough water to make 250 milliliters of solution. Explain each step and your calculations.

Step 1: Determine the Molar Mass of Na_2SO_4

To calculate the molarity, we first determine the molar mass of sodium sulfate (Na_2SO_4):
- Atomic mass of Na (Sodium) = 22.99 g/mol
- Atomic mass of S (Sulfur) = 32.07 g/mol
- Atomic mass of O (Oxygen) = 16.00 g/mol

$$\text{Molar mass of Na}_2\text{SO}_4 = (2 \times 22.99) + (1 \times 32.07) + (4 \times 16.00) \tag{2}$$

$$= 45.98 + 32.07 + 64.00 = 142.05\,\text{g/mol} \tag{3}$$

Step 2: Calculate the Moles of Na_2SO_4

Using the formula:

$$\text{Moles} = \frac{\text{Mass of solute (g)}}{\text{Molar mass (g/mol)}} \tag{4}$$

$$\text{Moles of Na}_2\text{SO}_4 = \frac{14.2}{142.05} = 0.1\,\text{moles} \tag{5}$$

Step 3: Calculate the Molarity

Molarity (M) is defined as:

$$M = \frac{\text{Moles of solute}}{\text{Liters of solution}} \tag{6}$$

Since 250 mL = 0.250 L,

$$M = \frac{0.1}{0.250} = 0.4\,\text{M} \tag{7}$$

Summary

The molarity of the Na_2SO_4 solution is **0.4 M**. This calculation follows three steps: determining molar mass, calculating the moles of solute, and applying the molarity formula. This method is essential in preparing and standardizing chemical solutions in laboratories and industrial processes.