A Rigid, Insulated Tank That Is Initially Evacuated Is Connected Through A Valve To A Supply Line That

Introduction

A Rigid, Insulated Tank That Is Initially Evacuated Is Connected Through A Valve To A Supply Line That presents a classic scenario in thermodynamics and fluid mechanics, often encountered in industrial processes, refrigeration cycles, and energy systems. This setup involves a tank that is perfectly rigid (i.e., its volume remains constant) and insulated (no heat transfer occurs with the surroundings). Initially, the tank is evacuated, meaning it contains a vacuum with negligible pressure and density. When connected to a supply line through a valve, the system undergoes dynamic changes driven by pressure differences, fluid flow, and thermodynamic principles. The analysis of such a system involves understanding the transient behavior, equilibrium conditions, and the resulting thermodynamic states.

This article provides an in-depth exploration of the physical phenomena, thermodynamic concepts, and mathematical modeling relevant to this scenario, offering insight into the processes that occur when the valve is opened and fluid begins to flow into the evacuated tank.

Initial Conditions and System Description

Characteristics of the Rigid, Insulated Tank

- Rigidity: The volume of the tank remains constant throughout the process.
- Insulation: No heat transfer occurs between the tank and its surroundings, implying adiabatic conditions.
- Initial Evacuation: The interior is a vacuum, with negligible pressure, temperature, and density.

Supply Line and Its Conditions

- The supply line contains a fluid—could be a pure substance, mixture, or ideal gas—with known initial pressure, temperature, and composition.
- The fluid may be at a higher pressure than the evacuated tank, leading to flow upon valve opening.
- The supply line is assumed to be large enough or well-connected to maintain constant conditions during the process, i.e., it acts as a reservoir or source.

Connection Through a Valve

- The valve is initially closed.
- When opened, it allows fluid to flow from the supply line into the evacuated tank.
- The valve may be modeled as instantaneous opening or gradual opening, but for ideal analysis, instantaneous opening is often assumed.

Physical Phenomena During the Process

Flow Dynamics and Shock Waves

- The sudden opening causes a rapid movement of fluid into the tank.
- Depending on the pressure difference, the flow can be subsonic or supersonic.
- In some cases, shock waves may form within the flow path, especially if the pressure ratio is large.

Pressure and Temperature Changes

- The incoming fluid's pressure and temperature influence the final state inside the tank.
- The process may involve adiabatic expansion or compression, depending on the conditions.

Mixing and Equilibration

- Once fluid enters the evacuated tank, it mixes with the initial vacuum (negligible matter, so the process is essentially filling).
- The final state in the tank depends on the thermodynamic properties of the fluid, initial conditions, and the nature of the process.

Thermodynamic Analysis of the Process

Assumptions for Simplified Modeling

- Adiabatic process: No heat transfer to or from the surroundings.

- No work transfer: Since the tank is rigid, boundary work is zero.
- Steady flow during valve opening: For modeling, often assumed as a quasi-steady process during the flow.
- Idealized fluid behavior: Depending on the fluid, ideal gas law or real fluid property data may be used.

Energy Balance in the Rigid, Insulated Tank

Given the assumptions:

- Initial energy in the tank: Zero, as it is evacuated.
- Final energy in the tank: Due to the mass of fluid entering and the associated internal energy.

The energy balance can be expressed as:

$$
0 = \text{Work} + \text{Heat transfer} + \text{Change in internal energy}
$$

Since the tank is rigid and insulated:

$$
\Delta U_{tank} = m_{tank} u_{final}
$$

and

$$
\text{Work} = 0,\quad \text{Heat transfer} = 0
$$

Thus, the change in internal energy corresponds to the energy brought in by the fluid entering the tank.

Mass and Momentum Considerations

- Mass flow rate depends on the pressure difference and the flow characteristics through the valve.
- The flow can be approximated using isentropic flow equations or orifice flow equations depending on whether the flow is choked or unchoked.

Final Equilibrium State

- The final pressure, temperature, and internal energy inside the tank are determined by the mass and energy of the fluid that entered.
- If the supply line conditions are known and the process is adiabatic and isentropic, the final state inside the tank can be calculated using thermodynamic relations.

Mathematical Modeling of the Process

Flow Through the Valve

- The mass flow rate ($\dot{m}$) can be modeled as:

$$
\dot{m} = C_d A \sqrt{\frac{2 \Delta P}{\rho}}
$$

where:

- C_d: Discharge coefficient
- A: Cross-sectional area of the valve
- ΔP: Pressure difference between supply line and tank
- ρ: Density of the fluid in the supply line

- For choked flow, the flow reaches sonic velocity at the vena contracta, and mass flow rate becomes:

$$
\dot{m} = C_d A P_{up} \sqrt{\frac{\gamma}{R T_{up}}} \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma + 1}{2(\gamma - 1)}}
$$

where:

- P_{up}: Upstream (supply line) pressure
- T_{up}: Upstream temperature
- γ: Specific heat ratio
- R: Specific gas constant

Final State Calculations

- The final pressure inside the tank (P_{final}) can be found assuming the fluid is ideal:

$$
P_{final} V = m_{total} R T_{final}
$$

- The energy conservation in the process:

$$
m_{total} u_{final} = \text{initial energy} + \text{energy of incoming fluid}
$$

- For ideal gases, the internal energy:

$$
u = C_v T
$$

- The temperature and pressure are related via the ideal gas law:

$$
P_{final} = \frac{m_{total} R T_{final}}{V}
$$

- The process continues until the pressure inside the tank equals the supply line pressure or until the flow ceases.

Final State and System Behavior

Equilibrium Conditions

- When the pressure inside the tank equals the supply line pressure, flow stops.
- The final temperature and pressure are uniform throughout the tank due to perfect mixing.

Implications of the Final State

- The final pressure, temperature, and density are functions of the initial supply line conditions and the amount of fluid that entered.
- The process can be used for controlled filling, pressurization, or inerting applications.

Effect of Multiple or Continuous Fillings

- If the supply line remains connected and the process continues, the tank gradually reaches the supply line conditions.
- Transient analysis may be needed for dynamic systems with varying supply conditions.

Practical Applications and Considerations

Industrial Relevance

- Filling compressed gas cylinders
- Inerting tanks with inert gases
- Pressurizing vessels in chemical plants
- Refrigeration system charging

Design Considerations

- Valve sizing to achieve desired flow rates
- Material compatibility with fluids
- Ensuring safety against overpressure
- Controlling flow to prevent shock waves or damage

Limitations and Assumptions in Modeling

- Idealized flow assumptions may not hold in real systems.
- Heat transfer, although neglected here, may influence the final state.
- Non-ideal fluid behaviors require detailed property data.

Conclusion

Connecting a rigid, insulated, initially evacuated tank to a supply line through a valve involves complex thermodynamic and fluid dynamic phenomena. The process is governed by the initial conditions, the properties of the fluid, the characteristics of the flow path, and the thermodynamic principles of energy conservation, mass flow, and equilibrium.

Understanding this process enables engineers to design systems for safe and efficient filling, pressurization, and inerting applications. By applying idealized models alongside empirical data, it is possible to predict the final states, optimize flow rates, and ensure system safety. While simplifications such as neglecting heat transfer and assuming ideal flow provide valuable insights, real-world applications often require more detailed analysis considering non-idealities, transient effects, and safety margins.

Overall, the scenario encapsulates fundamental principles of thermodynamics and fluid mechanics, illustrating the intricate interplay between physical laws and engineering design in practical systems.

Frequently Asked Questions

What are the typical uses of a rigid, insulated tank connected to a supply line?

Such tanks are commonly used for storing and maintaining specific gas or liquid conditions, often in refrigeration, chemical processing, or cryogenic applications, where insulation minimizes heat transfer and the tank's rigidity maintains its shape under varying pressures.

How does connecting an evacuated, insulated tank to a supply line affect its internal pressure?

When connected, the supply gas or fluid flows into the evacuated tank, increasing its internal pressure until equilibrium is reached, depending on the supply pressure and the tank's volume and insulation properties.

What role does insulation play in the thermal behavior of the tank during connection?

Insulation minimizes heat exchange with the environment, helping to maintain the internal temperature, which affects pressure stability and the rate at which the tank equilibrates with the supply line conditions.

What are the thermodynamic processes involved when the tank is **connected to the supply line?**

The process involves fluid flow into the tank, possibly involving adiabatic compression or expansion, and heat transfer depending on insulation effectiveness, leading to changes in pressure and temperature inside the tank.

How does the initial evacuation of the tank influence the filling process when connected to the supply line?

The initial evacuation creates a low-pressure environment inside the tank, resulting in rapid gas inflow upon connection, which can cause pressure and temperature changes as the tank fills and approaches equilibrium.

What safety considerations are important when connecting an evacuated, insulated tank to a supply line?

Safety precautions include ensuring pressure ratings are not exceeded, controlling flow rates to prevent rapid pressure changes, verifying insulation integrity, and monitoring temperature and pressure to prevent tank rupture or leaks.

How does the process differ if the supply line contains a compressible gas versus an incompressible fluid?

For gases, pressure and temperature changes are significant during transfer due to compressibility, leading to thermodynamic effects like cooling or heating. For incompressible fluids, changes are primarily related to pressure head and flow rate, with less impact on temperature.

What equations govern the pressure and temperature changes during the connection process?

The process can be described by the ideal gas law (PV=nRT), conservation of energy, and principles of thermodynamics such as adiabatic or isothermal processes, depending on the specifics of the system and insulation properties.

Additional Resources

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Introduction

The study of thermodynamic systems involving tanks connected to supply lines is fundamental in understanding fluid mechanics, heat transfer, and energy conservation principles. When considering a rigid, insulated tank that is initially evacuated, the system exhibits unique behaviors during the process of connection and subsequent fluid flow from the supply line. This scenario is common in industrial applications such as gas storage, cryogenics, and process engineering, where precise control and understanding of pressure, temperature, and mass transfer are essential. This comprehensive review delves into the physical setup, thermodynamic principles, process sequences, and analytical considerations involved in such a system.

Physical Setup and Initial Conditions

Description of the System

- Rigid Tank:
- The tank's volume remains constant throughout the process, implying that the physical boundaries are immovable.
- The rigidity ensures that any pressure or temperature changes inside the tank are solely due to fluid interactions and not volume alterations.

- Insulated Walls:
- The tank's walls are thermally insulated, meaning no heat transfer occurs between the tank interior and the environment.
- Insulation simplifies the analysis by eliminating heat exchange, focusing solely on work and internal energy changes.

- Initial Evacuation:
- The tank is initially evacuated, implying it contains a vacuum or near-zero pressure state, effectively removing any gas or fluid inside at the start.
- This initial state is crucial because it sets the baseline for pressure and temperature after the connection.

- Connection via a Valve:
- The tank is connected through a valve to a supply line that contains a fluid (liquid or gas).
- The valve can be opened or closed to control the flow, often assumed to be instantaneous or controlled based on the analysis.

Initial Conditions

- Inside the Tank:
- Pressure: Approximately zero (vacuum).
- Temperature: Usually considered undefined initially but can be assumed to be at some ambient or specified temperature upon fluid contact.

- Supply Line Conditions:
- Contain a fluid at known pressure P_s, temperature T_s, and possibly known composition.
- The fluid may be at a high or low pressure relative to the tank, depending on the scenario.

- Assumptions for Simplification:
- The fluid in the supply line is in thermodynamic equilibrium.
- The process takes place under idealized conditions, neglecting effects like friction, turbulence, or non-ideal fluid behavior unless specified.

Thermodynamic Principles Governing the Process

Conservation of Mass

- The mass inside the tank initially is zero.
- When the valve is opened, fluid begins to flow into the tank, increasing its mass over time.
- The mass transfer rate depends on the pressure difference, valve characteristics, and fluid properties.

Conservation of Energy

- Since the tank is insulated, heat transfer across the walls is zero, simplifying the energy balance to account for work and internal energy changes.
- The inflow of fluid can do work (via pressure and momentum transfer) and change the internal energy of the system.

First Law of Thermodynamics (Energy Balance)

For the entire system (tank + inflowing fluid):

$$
\Delta U_{system} = Q - W_{system}
$$

- Given insulation: $Q = 0$.
- The change in internal energy depends on the fluid's mass, pressure, and temperature.
- The inflow of fluid introduces energy into the tank, altering its internal energy and possibly generating

pressure and temperature changes.

Second Law of Thermodynamics

- The process involves entropy considerations, especially during the rapid filling of the evacuated tank.
- The process may be irreversible, especially if the flow is rapid or involves shock waves or turbulence.

Idealizations and Simplifications

- Quasi-Static Assumption:
- Often, the process is considered quasi-static for analytical simplicity, implying that the system passes through a series of equilibrium states.

- Isentropic or Isothermal Assumptions:
- Depending on the scenario, the inflow may be treated as isentropic (adiabatic and reversible) or involve heat exchange (which is zero here due to insulation).

Process Sequence and Phenomena

Valve Opening and Initial Inrush

- When the valve is suddenly opened, the high-pressure fluid from the supply line begins to enter the evacuated tank.
- Since the tank is initially at vacuum, the initial inrush of fluid can be rapid, possibly producing shock waves or compression waves depending on the flow regime.

Flow Regimes and Shock Phenomena

- Choked Flow:
- If the pressure difference is sufficiently large, the flow may become choked, meaning the fluid velocity reaches the speed of sound at some point in the flow path.
- This limits the mass flow rate into the tank.

- Shock Waves:
- Rapid filling can cause shock waves to propagate within the fluid or at the interface, especially if the fluid is a compressible gas.
- These phenomena influence the pressure and temperature distribution during the filling process.

Filling Dynamics

- Pressure Build-Up:
- As fluid enters, the pressure inside the tank increases from vacuum towards the supply line pressure, possibly passing through intermediate states.

- Temperature Changes:
- For gases, rapid compression or expansion influences temperature; in adiabatic compression, temperature rises, while expansion or mixing can cause cooling or heating.

- Flow Velocity and Turbulence:
- The inflow velocity depends on the pressure differential and the geometry of the connecting pipe and valve.

Equilibrium State

- The process continues until the pressure inside the tank equilibrates with the supply line pressure (assuming no further flow or a steady-state condition).
- The final state depends on many factors, including the nature of the fluid, initial conditions, and whether the process is adiabatic or involves heat transfer.

Analytical and Modeling Approaches

Idealized Models

- Isothermal Filling:
- Assumes the temperature remains constant during the filling process, suitable when heat exchange occurs rapidly or the process is slow.

- Adiabatic Filling:
- Assumes no heat exchange, focusing on energy conservation within the system, relevant for rapid filling scenarios.

- Quasi-Static Approximation:
- Treats the process as a sequence of equilibrium states, simplifying the analysis of pressure, temperature, and internal energy changes.

Governing Equations

1. Mass Balance:

$$
\frac{dm}{dt} = \dot{m}_{in}
$$

where $\dot{m}_{in}$ is the mass flow rate into the tank.

2. Energy Balance:

$$
\frac{dU}{dt} = \dot{Q} - \dot{W}
$$

with $\dot{Q} = 0$ (insulation), and $\dot{W}$ includes flow work.

3. Pressure and Temperature Relations:
- For ideal gases: $PV = mRT$
- For real fluids: use appropriate equations of state.

Computational and Experimental Methods

- Computational Fluid Dynamics (CFD):
- Simulate the transient flow, shock formation, and pressure/temperature profiles.

- Experimental Techniques:
- Use pressure sensors, thermocouples, and flow meters to monitor the filling process.

Implications and Applications

Industrial Relevance

- Cryogenics and Gas Storage:
- Filling evacuated tanks with liquefied gases or gases at high pressure.

- Process Engineering:
- Controlled filling of reactors or pressure vessels.

- Safety Considerations:
- Rapid filling can cause pressure surges, potential shock waves, or structural stress.

Design Considerations

- Valve Sizing:
- To control flow rate and avoid sudden pressure spikes.

- Tank Insulation Quality:

- Determines the thermal behavior during filling.

- Materials and Structural Integrity:
- Must withstand pressure fluctuations during the process.

Control Strategies

- Gradual Valve Opening:
- To mitigate shock waves and pressure surges.

- Pressure Regulation:
- Using pressure relief devices or controlled pressure drops.

Summary and Conclusions

The scenario of a rigid, insulated tank that is initially evacuated and connected through a valve to a supply line presents a complex interplay of fluid mechanics, thermodynamics, and heat transfer. The key points include:

- The initial vacuum state creates a significant pressure gradient that drives rapid fluid inflow when the valve is opened.

- The process involves transient phenomena such as shock waves, flow choking, and rapid pressure and temperature changes, especially for compressible fluids.

- Simplified models assuming adiabatic and quasi-static processes aid in initial analysis but may need refinement for real-world applications involving non-idealities.

- Practical applications require careful control of flow rates, insulation considerations, and structural integrity to ensure safety and efficiency.

- Advanced modeling techniques, including CFD and experimental validation, are essential for capturing the detailed dynamics.

Understanding these principles is vital for engineers designing systems involving evacuated tanks and supply lines, ensuring safe operation, optimal performance, and reliable control of fluid transfer processes.

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