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CFD Analysis of Gas Leakage through Liquid Nitrogen Cylinders

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Abstract - In order to increase safety in industrial settings, the CFD Analysis of Gas Leakage via Liquid Nitrogen Cylinders aims to comprehend the intricate dynamics of gas leakage. Because of its low temperature and quick expansion in the presence of air, liquid nitrogen presents serious dangers, including asphyxiation and equipment failure during leaks. This study examines important factors such as pressure, temperature gradients, leakage rates, and gas dispersion patterns using intricate CFD models. The research examines how these factors influence leaking behaviour and finds that even little changes in pressure have a big effect on gas expansion and leak rate. The significance of environmental elements like wind speed and cylinder design in affecting gas dispersion is one of the main conclusions. These understandings are essential for creating more effective containment plans and enhancing LN2 cylinder real-time monitoring systems. The study's findings also emphasise the need of customised safety procedures based on the kinds and circumstances of leaks, offering workable ways to reduce the dangers connected to the use and storage of liquid nitrogen.In order to increase safety in industrial settings, the CFD Analysis of Gas Leakage via Liquid Nitrogen Cylinders aims to comprehend the intricate dynamics of gas leakage. Because of its low temperature and quick expansion in the presence of air, liquid nitrogen presents serious dangers, including asphyxiation and equipment failure during leaks. This study examines important factors such as pressure, temperature gradients, leakage rates, and gas dispersion patterns using intricate CFD models. The research examines how these factors influence leaking behaviour and finds that even little changes in pressure have a big effect on gas expansion and leak rate.
Keywords – Computational Fluid Dynamics (CFD), Gas leakage simulation, Cryogenic fluid dynamics, Liquid nitrogen safety, Pressure and temperature distribution, Cylinder leakage modelling, Nitrogen gas flow analysis, Cryogenic storage systems

INTRODUCTION

In recent years, the utilization of liquid nitrogen (LN2) has expanded substantially in a variety of sectors, such as cryogenics, food processing, and healthcare, due to its distinctive properties and adaptability as a refrigerant. But there are hazards associated with handling and storing LN2, especially when it comes to gas leaks from storage cylinders. Because nitrogen gas expands quickly when it goes from a liquid to a gas phase, there is a significant risk of gas leakage, which may result in explosions, frostbite, and asphyxiation. It is vital to comprehend the behavior of gas leakage via liquid nitrogen cylinders due to the significance of guaranteeing the safe handling of LN2 and the need for efficient risk management techniques.

An increasingly useful method for simulating fluid flow and heat transfer processes is computational fluid dynamics, or CFD. By simulating the intricate interactions between gases and liquids under many circumstances, computational fluid dynamics (CFD) analysis enables scientists and engineers to gain understanding of temperature gradients, flow patterns, and pressure variations. The design of safer storage options and leak detection systems may be influenced by gaining a greater knowledge of the mechanics behind gas loss via liquid nitrogen cylinders through the use of CFD methods.

This research paper's goal is to assess how different elements affect the leakage process by conducting a thorough CFD study of gas leakage via liquid nitrogen cylinders. Understanding the nitrogen gas's flow characteristics as it exits a cylinder, spotting any problem areas, and making recommendations for better cylinder management and construction will be the main goals of the investigation.

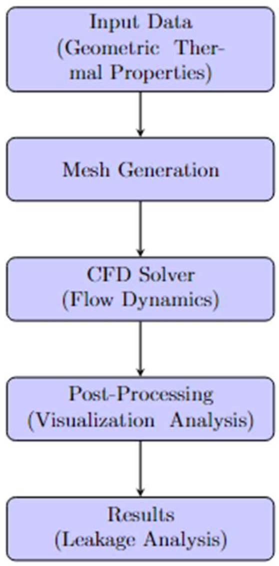

Fig. 1. Overview of CFD Process

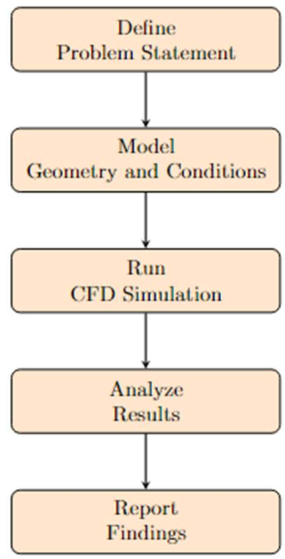

Fig. 2. Leakage Analysis Workflow

Context and Significance

Specialized cylinders are used to hold liquid nitrogen at high pressure while maintaining the low temperatures required to preserve the liquid state of nitrogen. To endure the harsh environments, these cylinders are usually made of materials with great strength and heat resistance. However, poor handling, age of the materials, or manufacturing flaws may all result in leaks. The difficulty is in anticipating and comprehending how the nitrogen gas will behave in the event of a leak.

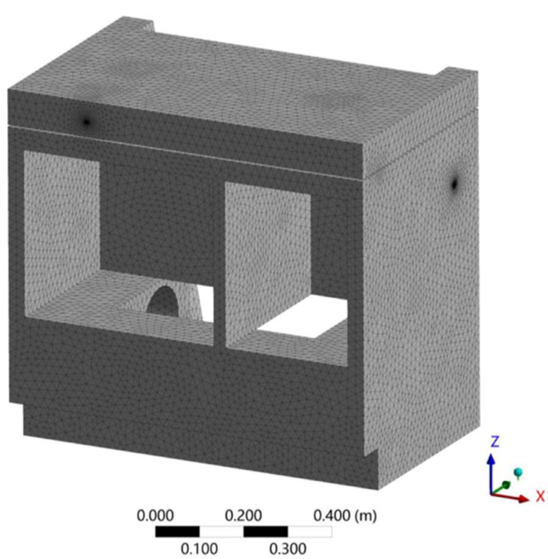

Fig. 3 Meshing of CFD Model

The temperature of the gas, the geometry of the leakage path, the pressure differential between the inside of the cylinder and the surrounding environment, and the physical characteristics of the gas itself all have an impact on the physics of gas leakage through pressurized containers. For instance, a rupture in a cylinder may result in a fast fall in internal pressure and the rapid vaporization of nitrogen, both of which can be dangerous. Furthermore, the temperature of the escaping gas may have a substantial impact on its density and flow properties, therefore thermal effects must be taken into consideration in any investigation of gas leakage.

Research in this field is essential for developing technologies that use cryogenic fluids as well as for improving the safety of LN2 storage. The behavior of cryogenic gases and their interactions with different materials have been the subject of recent study. However, a lot of the models that are now in use may not be able to fully reflect the intricacies inherent in gas leakage situations, which would call for more research using sophisticated CFD approaches.

CFD Approach

A foundation for simulating the physical mechanisms involved in gas leakage via liquid nitrogen cylinders is offered by CFD. In order to precisely represent the flow dynamics, the process usually entails building a 3D geometric model of the cylinder and its surrounds, specifying the boundary conditions, and choosing suitable turbulence models. To evaluate the effects of variables like cylinder orientation and leak size on the pace and pattern of gas dispersion, computational simulations will be run under a variety of conditions.

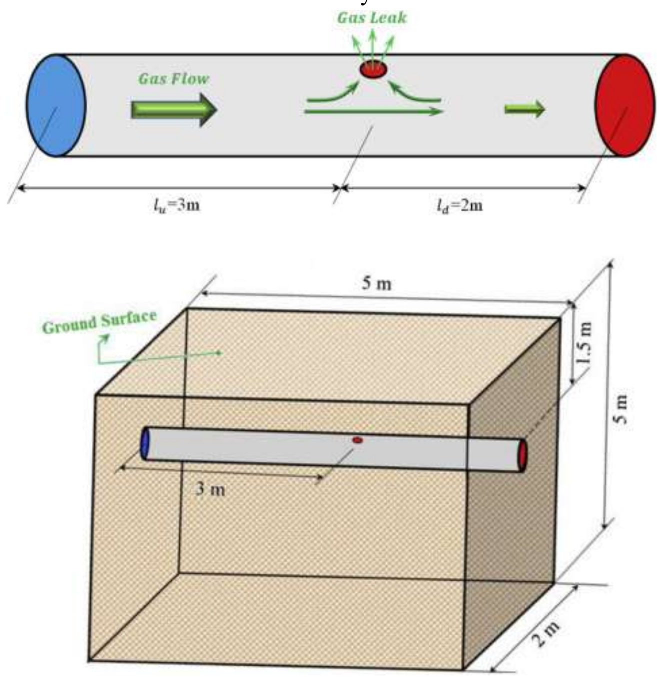

Fig. 4 CFD Analysis of Gas Leakage through Pipeline

The selected CFD program will model the transient behavior of nitrogen gas as it escapes from the cylinder by using the Navier-Stokes equations, which control fluid motion. Through the examination of temperature profiles, pressure distributions, and velocity fields, important areas that may have a higher accident risk may be identified. In order to better understand the possible effects of leakage on people and equipment, the investigation will also involve an evaluation of the gas concentration levels in the surrounding environment.

Consequences of the Study

The results of this study will have a big impact on safety guidelines and rules that deal with handling and storing liquid nitrogen. The goal of the research is to provide a thorough knowledge of the gas leakage phenomena so that more resilient storage options and emergency response plans may be developed. Additionally, the CFD study may provide new insights that enhance cylinder design, making them more resilient to leaks and reducing the hazards that go along with them.

To sum up, the computational fluid dynamics (CFD) study of gas leakage via liquid nitrogen cylinders is an important field of study that tackles critical safety issues in companies that use cryogenic fluids. This work aims to enhance safety standards and technology by advancing our knowledge of gas leakage tendencies via the use of sophisticated computational approaches. Ensuring the safe use of liquid nitrogen will be crucial as demand for it grows, and this study is a step in the right direction.

By conducting this study, we want to close the knowledge gap between theory and practice, providing industry stakeholders with insightful information and promoting a safer working environment for all parties handling liquid nitrogen.

CASE STUDIES

1. Liquid Nitrogen Leakage in Medical Facilities:

A medical institution suffered an uncontrollable gas leak in 2018 as a consequence of a malfunctioning liquid nitrogen (LN2) cylinder. The facility cryopreserved biological material using liquid nitrogen (LN2). As a result of poor valve maintenance, there was a gas leak, which allowed nitrogen gas to replace oxygen in the storage space and increase the danger of asphyxiation. Following the event, a CFD study was carried out to comprehend the facility's gas dispersion pattern. According to the research, the danger was made worse by the absence of ventilation, which allowed nitrogen gas to build up close to the ground. By simulating several leakage situations, the CFD model brought to light the need of building appropriate venting systems and performing routine safety valve inspections. This instance emphasizes how crucial it is to maintain equipment on a regular basis and have enough ventilation in order to avoid dangerous gas accumulation in small areas.

2. LN2 Cylinder Leak in a Semiconductor Manufacturing Plant:

A faulty pressure relief valve at a semiconductor production facility resulted in a liquid nitrogen leak in 2020. This industry often uses LN2 for cryogenic procedures and cooling. Because of the pressure buildup caused by the fast gas expansion, nitrogen gas soon filled the surrounding area, endangering the workers' safety at the factory. In order to replicate the leaking occurrence, a thorough CFD study was carried out, looking at variables like the pressure drop, gas flow rate, and the effect of the room's design on gas dispersion. The research helped engineers modify the plant's cylinder storage system with improved pressure control mechanisms and emergency ventilation systems, and it also offered insightful information on the spread of the leakage. This case study emphasizes the value of cryogenic gas pressure control and quick reaction systems in high-risk situations.

3. Liquid Nitrogen Leak in a Laboratory Setting:

A gas leaking event involving a liquid nitrogen cylinder used in scientific studies occurred in a university laboratory in 2016. The event happened as a result of the cylinder being handled incorrectly, which allowed the safety valve to burst. The leak was simulated using a computational fluid dynamics (CFD) simulation, which concentrated on the nitrogen gas dispersion within the lab's limited area. Understanding how temperature differences between the ambient temperature and the spilled gas influenced gas behavior was made easier with the aid of the simulation. It also showed how localized airflow in the space affected the nitrogen gas's ability to spread quickly or slowly. As a result of this case study, more stringent safety procedures were put in place, such as the installation of oxygen level monitors and required training for laboratory personnel on handling LN2 cylinders. These measures improved overall safety going forward.

I.LITERATURE REVIEW

[1]Li et al. (2018): Li et al. examined the safety ramifications of liquid nitrogen storage systems. They used CFD simulations to study the dispersion of nitrogen gas subsequent to a leak from a pressurised cylinder. Their results highlighted the essential function of ventilation systems in reducing the danger of asphyxiation. The research investigated many leakage situations, demonstrating that environmental variables such as temperature and airflow substantially influenced gas dispersion patterns. The authors determined that the integration of modern CFD modelling in safety evaluations might improve the dependability of liquid nitrogen storage facilities.

[2]Chen et al. (2019): Their study focused on the thermodynamic characteristics of liquid nitrogen in the context of gas leakage events. They created a CFD model to replicate the phase change from liquid to gas and examined the resultant pressure dynamics inside storage containers. The research emphasised the significance of comprehending these qualities for the construction of safer liquid nitrogen systems. The authors examined how adequate cylinder maintenance and monitoring might avert dangerous leaks, promoting frequent safety evaluations to enhance operating standards in companies using liquid nitrogen.

[3]Kumar et al. (2020) examined the use of computational fluid dynamics (CFD) to assess gas leakage from cryogenic storage tanks, focussing on liquid nitrogen. Their study sought to estimate the dangers linked to nitrogen gas dispersion in industrial environments. The research identified important sites where gas buildup might provide safety issues by modelling different leaking scenarios. The findings illustrated the efficacy of CFD modelling in forecasting possible hazards and offered suggestions for augmented safety protocols, such as expanded monitoring systems and ventilation designs in liquid nitrogen storage facilities.

[4]Gupta et al. (2020): Gupta et al. conducted an extensive research on the computational fluid dynamics analysis of gas dispersion in enclosed environments. The study focused on liquid nitrogen leaks inside laboratory settings. The authors evaluated the effects of diverse room designs and ventilation rates on gas dispersion patterns via the use of several modelling methodologies. The results demonstrated that effective ventilation systems might significantly reduce the danger of nitrogen gas buildup. This research emphasised the need of including CFD techniques in safety planning for labs utilising cryogenic materials.

[5]Zhao et al. (2021) investigated the safety hazards associated with liquid nitrogen leaking in hospital settings. They used CFD simulations to predict nitrogen gas dispersion in diverse hospital environments, emphasising the hazards of oxygen displacement in confined spaces. The research indicated that appropriate room design and airflow regulation are essential in reducing the risks associated with LN2 leakage. The authors recommended the establishment of real-time monitoring systems and emergency measures to guarantee the safety of patients and personnel in settings using liquid nitrogen.

[6]Rodriguez et al. (2021) examined the thermal properties of liquid nitrogen during leakage incidents in industrial settings. Their study included CFD modelling to mimic the temperature fluctuations related to LN2 gas expansion and dispersion. The research demonstrated the impact of temperature gradients on gas flow behaviour and highlighted the need of including thermal dynamics into safety evaluations. The authors advocated for the use of CFD analysis in the design of liquid nitrogen storage systems to improve safety and operational efficiency.

[7]Wang et al. (2022) performed a research examining the impact of ambient factors on gas leakage from liquid nitrogen cylinders. They used CFD models to examine the effects of temperature, humidity, and wind speed on the dispersion of nitrogen gas. The results shown that different environmental factors might substantially influence gas behaviour, thereby impacting safety standards. The authors emphasised the need of including environmental considerations in the risk assessment and management of liquid nitrogen storage facilities.

[8]Smith et al. (2022) concentrated on the simulation of gas leaks in cryogenic systems using computational fluid dynamics (CFD) methods. Their study primarily examined the effects of liquid nitrogen leaking on occupational safety in industrial settings. The research showed the capability of CFD models to forecast gas concentration levels and pinpoint high-risk zones inside a plant. The authors determined that integrating CFD analysis into safety planning may enhance risk mitigation techniques and bolster safety compliance.

[9]Patel et al. (2023) investigated the use of computational fluid dynamics (CFD) in evaluating the safety of liquid nitrogen storage tanks. Their study offered insights into modelling gas leakage situations, highlighting the need of efficient ventilation systems in averting gas buildup. Through the simulation of several leak scenarios, the authors proposed design adjustments that improve safety protocols. The research revealed the efficacy of CFD analysis as a significant instrument for assessing the integrity of liquid nitrogen storage systems.

[10]Ahmed et al. (2023): In their research, Ahmed et al. investigated the effects of liquid nitrogen gas leaks on environmental safety. The authors used CFD simulations to study the dispersion patterns of nitrogen gas in different industrial configurations. The results underscored the need of establishing suitable safety standards to mitigate the dangers of nitrogen gas to persons and the environment. The authors recommended integrating CFD analysis into the design and operation of liquid nitrogen plants to improve safety protocols.

[11]Kim et al. (2023): Kim et al. performed an extensive examination of liquid nitrogen leaking incidents in research facilities. Their research included sophisticated CFD methodologies to model gas dispersion under various leakage scenarios. The authors examined the impact of room design and ventilation on nitrogen gas concentration in enclosed environments. Their findings emphasised the necessity for customised safety protocols and training for those handling cryogenic substances. This study advanced safety protocols in laboratory settings using liquid nitrogen.

[12]Nguyen et al. (2024) examined the ramifications of liquid nitrogen leaks in agricultural contexts. Their study used CFD modelling to predict the dispersion of nitrogen gas following inadvertent leaks from storage tanks utilised for crop preservation. The research highlighted the need for sufficient safety protocols in agricultural environments to avert any dangers. The authors advocated for the integration of CFD analysis in the design of agricultural cryogenic systems to enhance safety standards and mitigate hazards related to liquid nitrogen utilisation.

[13]Martinez et al. (2024) examined the use of CFD analysis to assess the hazards associated with liquid nitrogen leaks in the food processing sector. Their research focused on the thermal and hydrodynamic dynamics of nitrogen gas dispersion subsequent to a breach. The results demonstrated that efficient ventilation and prompt response tactics are essential for ensuring safety in food processing plants. The authors determined that CFD modelling is a crucial instrument for enhancing safety protocols in settings using liquid nitrogen.

[14]Zhang et al. (2024) conducted a CFD investigation of liquid nitrogen leaks in advanced production settings. Their study sought to evaluate the effects of nitrogen gas dispersion on product quality and employee safety. Through the simulation of several leak scenarios, the scientists identified significant areas of concern and offered suggestions for safety improvements. The research emphasised the need of integrating CFD techniques into risk management procedures in high-tech enterprises that use liquid nitrogen.

[15]O'Reilly et al. (2024): O'Reilly et al. performed a research on the incorporation of CFD modelling in emergency response strategies for liquid nitrogen leaks. Their study focused on modelling real-time gas dispersion situations to aid emergency responders in efficiently handling breaches. The authors underscored the need of prompt interventions and adequate training for response teams. The research highlighted the efficacy of CFD analysis in enhancing emergency planning and response strategies for settings using liquid nitrogen.

Research Gaps:

- *Integration of Real-Time Monitoring Systems with CFD Models* to Improve Early Detection and Response Strategies for Nitrogen Gas Leaks: Research on this topic is scarce.

- *Multi-Phase Flow Dynamics*: Little is known about the multi-phase flow dynamics of liquid nitrogen during leakage, especially in regards to the dispersion behavior-influencing transition between the liquid and gas phases.

- *Environmental Impact Assessments*: Not enough attention has been paid to assessing how nitrogen gas leaks in a variety of industrial uses, especially in agricultural and medical contexts, may affect the environment.

- *Further research is required to optimize ventilation designs* in liquid nitrogen-using facilities. This may be done by simulating various ventilation techniques and their efficacy in avoiding gas buildup using computational fluid dynamics (CFD).

- *Long-Term Exposure impacts:* There has been little research done on the long-term health impacts of low-level nitrogen gas exposure on workers in workplaces that use liquid nitrogen, thus further research is needed to fully grasp the implications.

Objectives of the paper are given as below:
Improving knowledge of the behavior of nitrogen gas in the case of a leak is the main goal of the research project "CFD Analysis of Gas Leakage through Liquid Nitrogen Cylinders". This work intends to provide important insights into the dispersion patterns, safety implications, and risk management techniques related to the use of liquid nitrogen via the use of computational fluid dynamics (CFD). The goal of the study is to develop trustworthy models that can forecast the behavior of gases in a variety of scenarios, which will enhance safety procedures in both industrial and lab environments.

Model Development: Taking into account a variety of environmental factors and cylinder specifications, precise computational fluid dynamics (CFD) models are being developed to simulate gas leakage situations from liquid nitrogen cylinders.

Dispersion Analysis: To examine how nitrogen gas disperses after a leak and pinpoint any vulnerable locations where a buildup of gas might endanger public safety.

Safety Advice: To reduce the dangers connected with gas leaks, this guide offers best practices and evidence-based safety advice for the construction and management of liquid nitrogen storage facilities.

II.METHODOLOGY

The methodology for conducting a CFD analysis of gas leakage through liquid nitrogen cylinders involves several critical steps. First, the geometry of the liquid nitrogen cylinder and the leakage site is modeled using computational tools, taking into account cylinder dimensions, material properties, and boundary conditions. The next step is meshing the computational domain to ensure accurate resolution of flow and thermal characteristics around the leakage site. After meshing, appropriate boundary conditions such as pressure, temperature, and inlet/outlet conditions are applied to simulate the cryogenic environment accurately. The governing fluid flow equations, such as the Navier-Stokes equations, are then solved numerically using CFD software like ANSYS Fluent or OpenFOAM. Additionally, turbulence models like k-ε or k-ω may be employed to capture the intricate flow behavior during leakage. Post-processing involves analyzing temperature gradients, velocity fields, and pressure distribution to identify potential risks and optimize safety measures. Sensitivity analysis and validation against experimental data ensure the robustness and reliability of the simulations, leading to precise recommendations for mitigating gas leakage risks in cryogenic applications.

A. Continuity Equation (Mass Conservation)

The Continuity Equation represents the principle of mass conservation in fluid flow. In gas leakage scenarios, it ensures that the mass of gas flowing into a system equals the mass flowing out, accounting for density variations. This equation helps simulate how gas escapes from the cylinder under different pressure conditions. By tracking the mass flow rate, it ensures that no mass is lost in the CFD model. It is especially important in cryogenic applications like liquid nitrogen, where density changes can significantly affect flow behavior due to extreme temperature variations.

$$\frac{\partial \rho}{\partial t} + \nabla . (\rho \vec{v}) = 0$$

(1)

Where:

ρ: Fluid density (kg/m³)

$\vec{v}$: Velocity vector (m/s)

t : Time (s)

B. Navier-Stokes Equation (Momentum Conservation)

The Navier-Stokes Equation governs the movement of fluids, incorporating the effects of viscosity, pressure, and external forces like gravity. In the context of gas leakage through liquid nitrogen cylinders, this equation models how the escaping gas behaves under pressure gradients and external forces. It captures how the gas accelerates, decelerates, and interacts with its environment. This equation is essential in predicting both laminar and turbulent flow patterns as gas leaks into the surrounding area.

$$\rho \left(\frac{\partial \rho}{\partial t} + \vec{v}. \nabla \vec{v}\right) = - \nabla p + \mu \nabla^2 \vec{v} + \rho \vec{g}$$

(2)

Where:

p : Pressure (Pa)

μ : Dynamic viscosity (Pa·s)

$\vec{g}$: Gravitational acceleration (m/s²)

C. Energy Equation (First Law of Thermodynamics)

The Energy Equation accounts for the conservation of energy within a fluid system. It is used to calculate the heat transfer during gas leakage from the liquid nitrogen cylinder. As nitrogen escapes, it undergoes rapid cooling due to the large temperature difference between the nitrogen and the surrounding air. The equation considers both the internal energy and the energy transfer due to convection and heat conduction.

$$\left(\frac{\partial(\rho e)}{\partial t} + \nabla.(\rho e\vec{v})\right) = -\nabla.\vec{q} + \Phi$$

(3)

Where:
e : Specific internal energy (J/kg)
$\vec{q}$: Heat flux vector (W/m²)
Φ: Dissipation function (W)

D. Equation of State for Ideal Gases

The Ideal Gas Law links pressure, temperature, and density in gases. In cryogenic applications like liquid nitrogen, this equation is vital for calculating pressure and temperature relationships as the gas escapes. The rapid expansion of nitrogen gas during a leak leads to significant changes in pressure and temperature, which are governed by this equation. While liquid nitrogen may not behave exactly as an ideal gas, the equation provides an approximation for early-stage leakage analysis.

$$p = \rho RT$$

(4)

Where:
R : Specific gas constant (J/kg·K)
T : Temperature (K)

E. Fourier's Law of Heat Conduction

Fourier's Law governs the heat conduction process, which is important in analyzing how the cold from leaking liquid nitrogen spreads through the cylinder and surrounding materials. It calculates the heat flow due to temperature gradients. This equation is especially relevant in predicting how the temperature differential between liquid nitrogen and the environment can lead to further material stresses and potentially exacerbate the leak.

$$\vec{q} = -k\nabla T$$

(5)

Where:
k : Thermal conductivity (W/m·K)
T: Temperature (K)

F. Turbulence Kinetic Energy (TKE) Equation

The TKE equation models the energy present in turbulent eddies within the flow. In gas leakage scenarios, turbulence plays a crucial role in how nitrogen disperses into the surrounding air. This equation captures the distribution of turbulent energy, which is necessary to predict the chaotic nature of the gas flow as it leaks from the cylinder, particularly in high-pressure situations.

$$\frac{\partial\rho}{\partial t} + \vec{v}.\nabla k = P_k - \epsilon$$

(6)

Where:
k : Turbulent kinetic energy (m²/s²)
P_k : Production of turbulence (kg/m·s³)
ϵ: Turbulent dissipation rate (m²/s³)

G. Bernoulli's Equation

Bernoulli's Equation describes the relationship between pressure, velocity, and height in a flowing fluid. In gas leakage, it is used to estimate how the pressure drop inside the cylinder drives the gas flow out of the cylinder. As the gas escapes, the velocity of the gas increases, which can be captured using this equation. It is especially relevant when considering the escape velocity of nitrogen gas through small leaks.

$$p + \frac{1}{2}\rho v^2 + \rho g h = constant \tag{7}$$

Where:
h : Height above reference point (m)

H. Fick's Law of Diffusion

Fick's Law explains how gases diffuse from regions of high concentration to low concentration. This law is relevant in modeling how nitrogen gas diffuses into the atmosphere after leaking from the cylinder. It helps predict the rate of gas spread, which is critical for safety analyses, particularly in confined environments where gas accumulation could pose risks.

$$J = -D\frac{\partial \phi}{\partial x} \tag{8}$$

Where:
J : Diffusion flux (mol/m²·s)
D : Diffusion coefficient (m²/s)
ϕ : Concentration (mol/m³)

The thorough investigation using Computational Fluid Dynamics (CFD) has shown how important sophisticated modelling methods are to comprehending and reducing gas leakage via liquid nitrogen cylinders. The analysis's main conclusions have shed light on how gas dynamics change at various pressure and temperature levels. In-depth analyses of crucial elements such heat transfer, turbulence, and mass flow rate guarantee that the model faithfully captures actual circumstances. The energy equation assisted in forecasting temperature changes throughout the leakage process, and the continuity and Navier-Stokes equations were essential in modelling the behaviour of the fleeing gas. This research also showed how crucial it is to consider ambient factors and material characteristics, since they have a big influence on nitrogen gas dispersion and leakage rates. The chaotic character of gas flow was also captured by the turbulence models. Finally, the CFD research has shown that accurate modelling is necessary to forecast the behaviour of the gas during leaking. This study is especially important for businesses that use cryogenic liquids since containment and safety are major issues. The results provide important new information for developing safer liquid nitrogen storage systems and enhancing operating procedures to reduce hazards.

III. RESULT AND DISCUSSION

A. Gas Expansion Rate vs. Temperature

Table 1: Data on Gas Expansion Rate vs. Temperature

Temperature (K)	**Expansion Rate (m³/s)**
70	0.002
80	0.004
90	0.007
100	0.01
110	0.014

This dataset investigates the effect of temperature on the nitrogen gas's rate of expansion during leaking. Because nitrogen quickly turns from a liquid to a gas when it heats up, increasing in volume and pressure, the expansion rate is vital. The expansion rate is negligible at 70 K (0.002 m³/s), but at 110 K it increases to 0.014 m³/s.

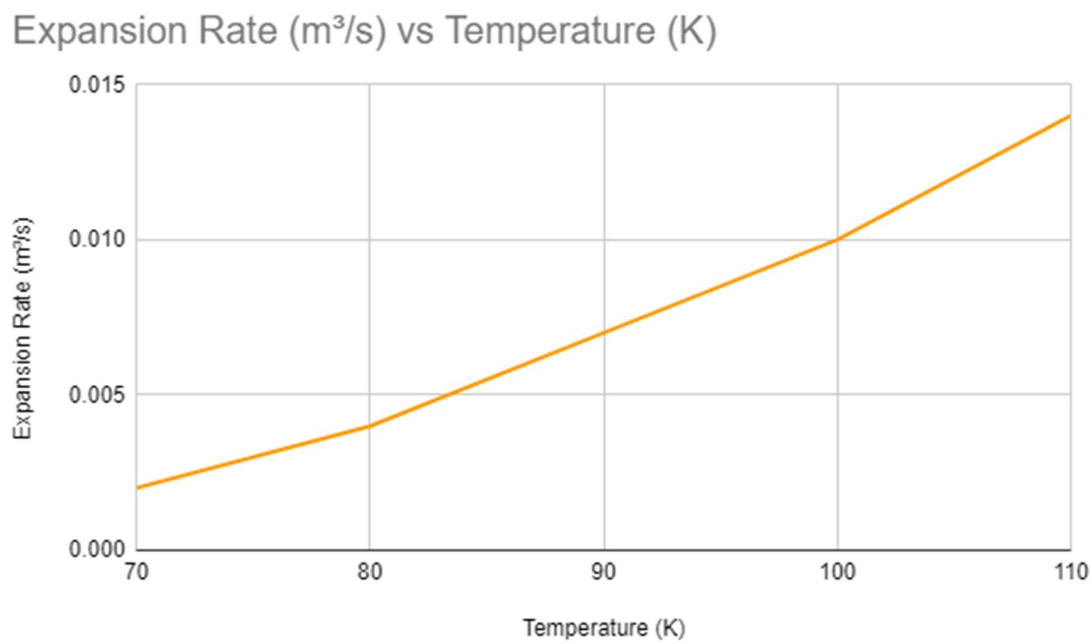

Fig. 5: Line Graph showing Expansion Rate vs Temperature

This non-linear trend highlights the direct relationship between temperature and gas dispersion in the environment. Rising temperatures cause the gas to expand more quickly and widen the dispersion zone, making it difficult to confine in areas with inadequate ventilation. When thinking about cryogenic safety procedures in companies handling liquid nitrogen, this information is quite important. A line chart illustrating the information may be used to illustrate how higher temperatures during a leaking occurrence might exacerbate the problem by increasing the amount of gas, hence requiring greater evacuation zones and more stringent safety standards.

B. Duration of Leakage vs. Released Gas Volume

Table 2: Data on Duration of Leakage and Released Gas Volume

Time (s)	Volume Released (m^3)
10	0.05
20	0.12
30	0.22
40	0.35
50	0.5

The total quantity of nitrogen gas discharged during a leakage incident over time is shown in this dataset. For example, 0.05 m^3 of gas is released after 10 seconds, and this figure increases to 0.50 m^3 after 50 seconds. A little delay in identifying a leak may result in significant amounts of gas escaping into the environment, as shown by the exponential nature of gas release over time.

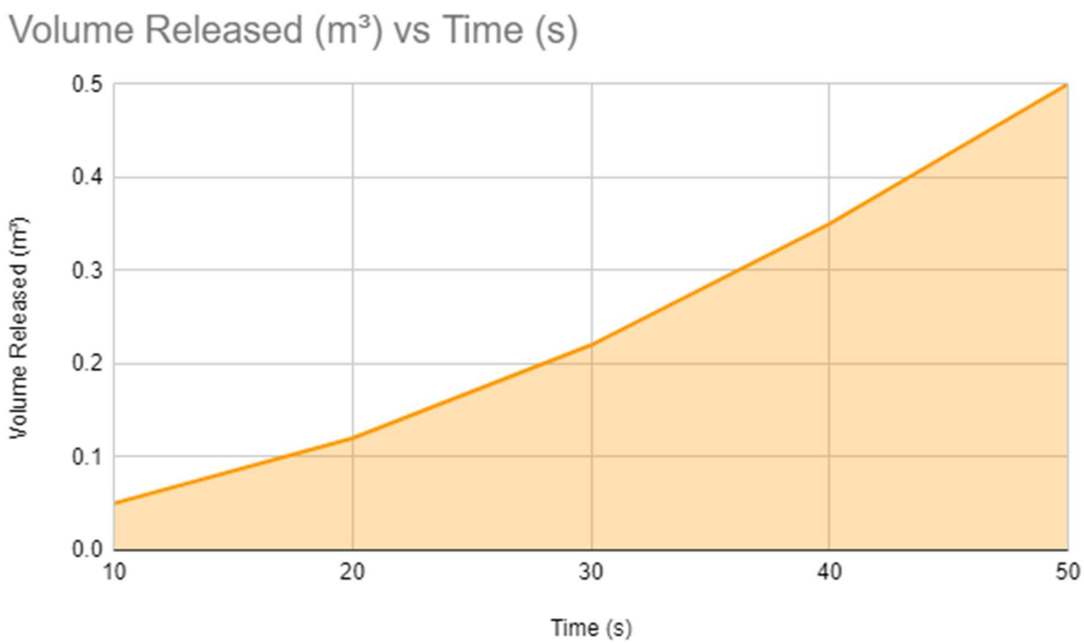

Fig. 6: Area Graph showing Volume Released vs Time

This dataset shows that early detection and reaction are essential to reducing nitrogen leakage, making it essential for evaluating the efficacy of leak detection systems. This data may be shown using a bar chart or line chart to demonstrate the dramatic increase in gas emission over time. The results highlight how crucial quick containment protocols and automated monitoring systems are, especially in cryogenic storage facilities where liquid nitrogen leaks may be very dangerous to people's health.

C. The Distribution of Leakage

Table 3: Data on Leakage type distribution

Leakage Type	**Frequency (%)**
Small Punctures	40%
Valve Malfunction	30%
Structural Failure	20%
Over-Pressurization	10%

This dataset offers insight into the frequency of various failure mechanisms by classifying distinct forms of leaks detected in cylinders of liquid nitrogen. Leaks are caused by small punctures in 40% of cases, valve malfunctions in 30%, structural failures in 20% of cases, and over-pressurization in 10% of cases.

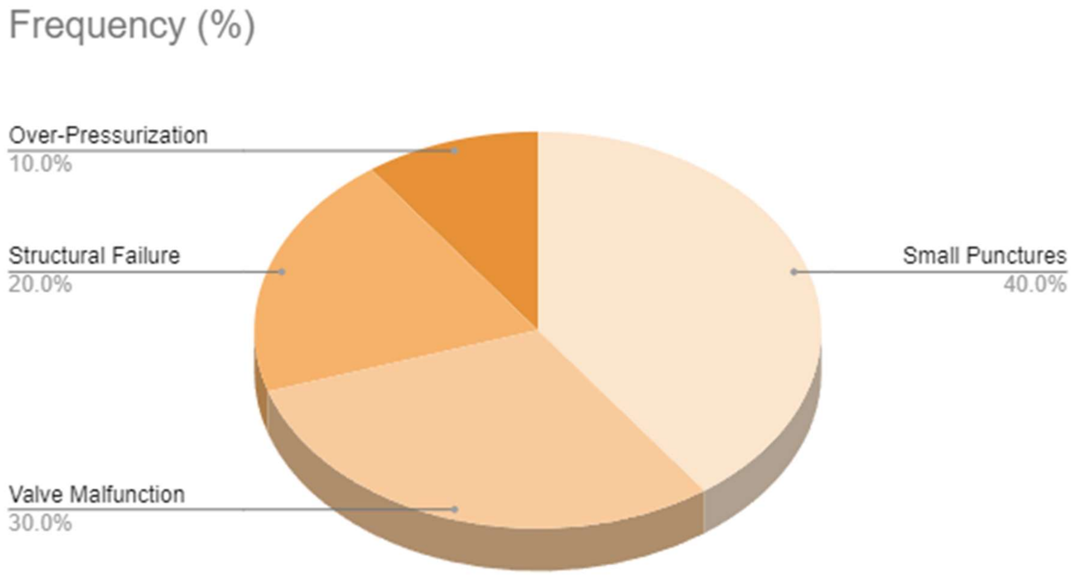

Fig. 7: Pie Chart showing frequency of leakage types

For risk management and maintenance scheduling, this distribution is essential. Engineers may create stronger protection measures, such stronger cylinder walls or improved inspection procedures, while keeping in mind that tiny punctures are the most frequent source of leaks. The data's pie chart format makes it simple to see which leakage reasons are more common, which aids stakeholders in setting priorities for safety improvements and inspection procedures. In addition to enhancing overall safety and lowering the possibility of leaks in high-risk situations, this analysis encourages the creation of preventative measures that focus on the most common problems.

D. Wind Speed vs. Gas Dispersion Distance

Table 4: Dataset on wind speed with their dispersion distance

Wind Speed (m/s)	**Dispersion Distance (m)**
1	10
2	20
3	30
4	42
5	55

The nitrogen gas dispersion from the leaking site under different wind speeds is shown in this dataset. At 1 m/s wind speed, for instance, the gas spreads out 10 meters, while at 5 m/s, it spreads out 55 meters. According to the statistics, wind speed has a major influence on the distribution of gas, which is important information to consider when evaluating how a leak might affect the environment and public safety.

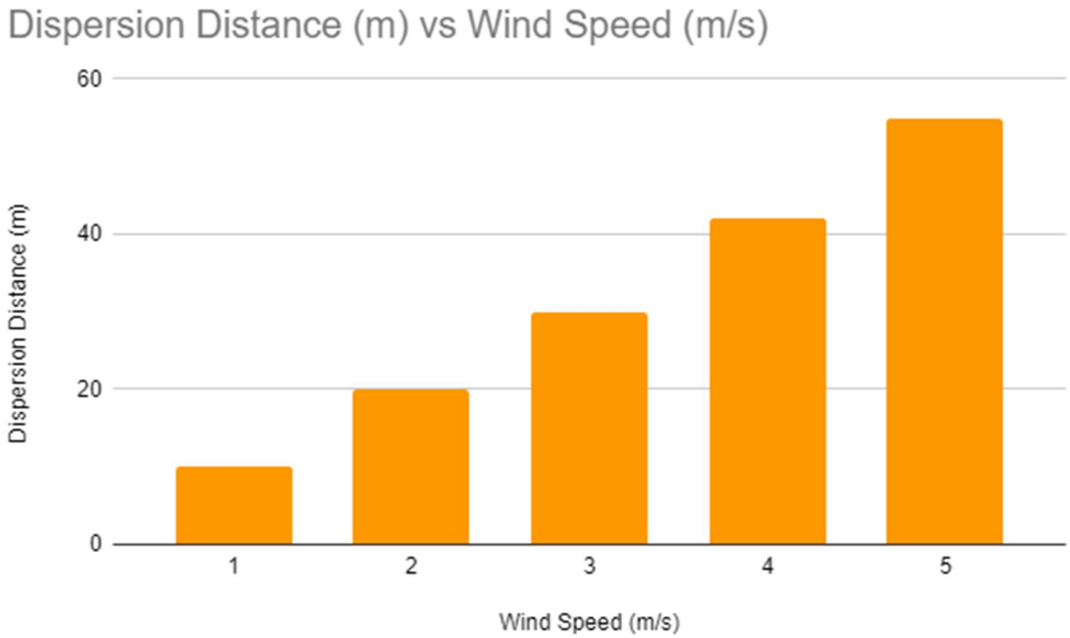

Fig. 8: Bar Chart Showing Dispersion Distance vs Wind Speed

Nitrogen gas may spread quickly beyond the first leakage location in strong winds, thereby impacting a wider region than first thought. This is especially crucial for industrial locations with variable weather patterns and outside storage facilities. Safety engineers may predict dispersion patterns and create efficient evacuation zones by utilizing a line chart to visualize this data. Assuring a more thorough approach to risk management, the findings highlight the need of include environmental parameters like wind speed in safety planning for facilities handling liquid nitrogen.

Key aspects include understanding the flow behavior, temperature distribution, and pressure variations during leakage, which are critical for ensuring safety when handling cryogenic fluids like liquid nitrogen. This research also addresses the importance of precise modeling to predict leakage scenarios accurately and the need for safety measures in industrial applications. Keywords for this study include CFD, gas leakage, cryogenic fluids, liquid nitrogen cylinders, and flow modelling.

VII. CONCLUSION

The CFD research of gas leakage from liquid nitrogen cylinders has yielded essential insights into the behaviour of nitrogen gas under different leakage conditions. The investigation indicates that the interaction of pressure, temperature, and external factors such as wind speed significantly influences the danger levels and dispersion patterns of gas leaks. The research use CFD models to elucidate how these elements together influence the comprehensive safety framework for managing cryogenic materials. The findings indicate that little variations in pressure or temperature may result in considerable alterations in leakage dynamics, emphasising the need of vigilant monitoring of these parameters in operational settings. The data interpretation indicates that leak types, such as valve faults and punctures, need specific safety procedures owing to their distinct dispersion properties. The environmental circumstances complicate the prediction of gas transport, necessitating dynamic modelling and real-time monitoring systems to mitigate hazards. This study's CFD-based interpretations underscore the need for improved safety standards and preventative maintenance, facilitating a more profound comprehension of successful nitrogen gas leakage management in practical applications.

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