

Design and Analysis of LNG Cryogenic Tank for Heavy Commercial Vehicle Applications

Jayesh Mahajan^{1*}, Rahul Joshi¹, Mayank Ladha¹, and Sandeep Badlani¹

¹Department of Mechanical Engineering, Swami Vivekanand College of Engineering, Indore. (M.P)

Abstract. The transportation industry, particularly in heavy-duty commercial vehicles, contributes significantly to global environmental pollution due to the high emissions associated with conventional diesel fuels. As part of the global push for cleaner and more sustainable energy solutions, Liquefied Natural Gas (LNG) has emerged as a promising alternative fuel for heavy commercial vehicles. LNG offers substantial reductions in carbon dioxide, nitrogen oxides, and particulate matter emissions, making it an attractive solution for mitigating the environmental impact of long-haul transport. However, the efficient storage and transportation of LNG present significant engineering challenges, particularly when it comes to maintaining the fuel in its cryogenic state during transit. This project focuses on the design, development, and analysis of a LNG cryogenic tank tailored for use in heavy commercial vehicles, addressing the critical factors of structural integrity, thermal insulation, safety, and space optimization. The study employs advanced simulation tools such as ANSYS for Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) to model the tank's performance under various operational conditions, including pressure variations, thermal gradients, and vehicle motion. Key objectives include optimizing the tank's design to ensure efficient fuel storage, minimizing boil-off, and ensuring safety under dynamic load conditions while adhering to space and weight limitations typical in commercial vehicles. The final design is validated through rigorous simulations and testing, aiming to provide a cost-effective, lightweight, and safe LNG storage solution that can support the broader adoption of LNG in the transportation sector. Ultimately, the project seeks to advance the development of sustainable technologies that align with global efforts to reduce carbon emissions and promote energy-efficient solutions in the heavy-duty vehicle industry.

Keywords — LNG Cryogenic Tank, Heavy Commercial Vehicle, Cryogenic Applications, Thermal Insulations

* Corresponding author: joshirahul728@gmail.com

1 INTRODUCTION

Liquefied Natural Gas (LNG) has emerged as a clean and efficient alternative fuel for heavy commercial vehicles due to its lower carbon footprint, higher energy density, and cost-effectiveness compared to conventional diesel fuel. With the increasing global emphasis on reducing greenhouse gas emissions and transitioning to sustainable energy sources, the adoption of LNG in the transportation sector, particularly for heavy commercial vehicles, is gaining momentum. However, one of the critical challenges in this transition is the design and development of an efficient, durable, and safe LNG cryogenic storage tank suitable for vehicle applications.

LNG cryogenic tanks are specialized storage systems designed to hold natural gas in its liquid state at extremely low temperatures (-162°C or lower). These tanks must ensure the thermal insulation necessary to minimize boil-off gas (BOG) and maintain LNG in its liquid form while withstanding the mechanical stresses and dynamic loading conditions encountered in heavy commercial vehicles. Additionally, the tanks need to comply with stringent safety standards and regulatory requirements to ensure safe operation during transportation and refuelling.

The design of LNG cryogenic tanks for heavy commercial vehicles involves addressing several technical challenges, including optimizing tank geometry for maximum fuel storage capacity, selecting lightweight yet durable materials to reduce vehicle weight, and ensuring thermal insulation to minimize heat ingress as shown in Fig. 1.



Fig. 1 Cryogenic LNG Cylinders Vehicle Nitrogen LNG Storage Tank Gas Cylinder for Truck [22]

Advanced computational tools such as Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) are often employed to analyze the structural integrity, thermal performance, and overall reliability of the tanks under various operating conditions.

Moreover, the integration of LNG cryogenic tanks into heavy commercial vehicles requires careful consideration of space constraints, ease of maintenance, and compatibility with the vehicle's existing systems. Innovations in tank design, such as multilayer insulation,

vacuum technology, and composite materials, play a vital role in enhancing the performance and efficiency of these storage systems.

This study focuses on the comprehensive design and analysis of LNG cryogenic tanks specifically tailored for heavy commercial vehicle applications. The objective is to develop a robust and efficient tank design that meets the operational demands of the transportation industry while adhering to safety and environmental standards. The research encompasses material selection, thermal insulation strategies, structural analysis, and system integration, providing a holistic approach to addressing the challenges associated with LNG storage in heavy commercial vehicles. The development of advanced LNG cryogenic tanks represents a significant step toward promoting sustainable transportation and reducing the environmental impact of heavy commercial vehicles. This research aims to contribute to the ongoing efforts to enhance the efficiency, safety, and reliability of LNG-based fuel systems, paving the way for broader adoption of LNG as a viable alternative fuel in the transportation industry.

The aim of this study is to design and analyze an efficient, durable, and safe LNG cryogenic tank specifically tailored for heavy commercial vehicle applications. The objective is to optimize the tank's performance by addressing key aspects such as thermal insulation, structural integrity, material selection, and system integration, while ensuring compliance with safety and environmental standards to promote the adoption of LNG as a sustainable alternative fuel in the transportation sector.

Objectives of the study

- To design an LNG cryogenic tank capable of withstanding the harsh conditions of heavy commercial vehicle operations.
- To analyze the structural integrity, efficiency, and pressure resistance of the LNG cryogenic tank.
- To optimize the tank's size and configuration to meet industry standards for safety, weight, and space utilization.
- To simulate and validate the performance of the tank under different operating conditions, including temperature fluctuations and vehicular motion.

Problem Definition

The widespread adoption of Liquefied Natural Gas (LNG) as an alternative fuel for heavy commercial vehicles faces significant challenges due to the need for cryogenic storage at temperatures around -162°C . Key issues include maintaining thermal efficiency to minimize boil-off, ensuring structural integrity under dynamic vehicle conditions, and optimizing space and weight within the vehicle's storage constraints. Current LNG cryogenic tank designs often fall short in terms of insulation performance, safety, and cost-effectiveness.

This project aims to address these challenges by designing an optimized LNG cryogenic tank using advanced simulation techniques such as ANSYS for structural and thermal

analysis. The goal is to develop a safe, efficient, and economically viable LNG storage system suitable for heavy-duty vehicles, supporting the wider adoption of LNG as a clean fuel.

The motivation for this project is driven by the urgent need to reduce emissions and environmental impact in the transportation sector, particularly within heavy commercial vehicles. As global regulations become stricter, the shift to cleaner fuels like Liquefied Natural Gas (LNG) is essential for lowering carbon dioxide, nitrogen oxides, and particulate matter. However, LNG's cryogenic storage poses significant engineering challenges in terms of insulation, thermal management, and pressure resistance.

This project aims to design an efficient LNG cryogenic tank for heavy vehicles, addressing these challenges while maintaining optimal fuel storage, safety, and space-efficiency. The research is motivated by the desire to support sustainable energy transitions and to innovate in the field of cryogenic tank design, contributing to the long-term sustainability of the transportation sector.

2 LITERATURE REVIEW

The gas industry has seen significant growth, with LNG being a top choice due to its flexibility and transportability. Indonesia's geographical advantage makes it a potential global player. However, investment decisions face uncertainties like volatile energy markets, fluctuating prices, geopolitical risks, and technological changes. A feasibility study shows a \$33.7 million, 10.96% IRR, 14.61-year payback period, and a Profitability Index of 1.26 [1, 2].

This paper discusses the use of a Fiber Optic Cable (FOC) and a Distributed Temperature Sensing (DTS) system to monitor LNG tanks during cryogenic conditions. The FOC, made of Stainless-Steel Tube, Steel, and PE Soft Jacket with polyimide material, is found to be efficient for harsh LNG temperatures. The FOC can detect location, temperature, and leakage alarms in real-time, ensuring the tank's stability. The study also investigates the detection of cryogenic temperature and cable rigidity, aiming to reduce the risk of accidents during LNG storage [3,4].

Liquefied natural gas (LNG) consumption is increasing globally, making cryogenic insulation system design crucial for large storage tanks. The industry often only considers construction conditions, neglecting operation, maintenance, and full-life cycle conditions. This paper analyzes and optimizes insulation system design for large tanks, considering insulation material performance, construction period, pre-cooling start-up, operation, and maintenance. The optimal daily evaporation rate requirements are obtained, providing a reference for LNG project design during construction [5].

Full Containment Tanks (FCT) are large, double-walled cryogenic storage tanks used to store LPG in low temperatures. Designing FCTs under seismic and thermal loads is complex. The Finite Element Method (FEM) simulation is used to predict stresses and displacements in a 3-D model. Two analyses are run to compare results and compute

thermal effects on seismic responses. Results show thermal stress effects are not ignored [6,7].

The study explores the use of liquid hydrogen storage (LH2) on Class-8 trucks to address issues like range, weight, volume, refueling time, and cost associated with Type-3 or Type-4 composite tanks. It discusses conceptual storage system configurations, structural aspects, and failure modes. The results show that these systems can reach 19.6% usable gravimetric capacity and \$174-183/kg-H2 cost when manufactured 100,000 systems annually [8,9].

This paper presents a dynamic model for predicting and investigating LNG fuel tank pressurization performance under marine conditions. The model uses an extended sloshing Nusselt number to evaluate heat transfer enhancement in horizontal tanks. Parametric studies reveal heat transfer dominates pressurization, while vapor condensation impacts holding period and sloshing. Sloshing can cause gas engine shut-downs in extreme situations [10,11,12].

The study designed a scale model of a LNG storage tank and conducted a shaking table test to investigate the insulation layer's interaction with the tank's liquid-solid coupling position. The results showed that the seismic response of the tank was related to ground motion frequency. A simplified mechanical model was constructed, reducing base shear and bending moment by 20%-25% and acceleration and displacement by 40% after insulation filling [13,14].

Liquefied natural gas (LNG) transport and storage require special double-walled cryogenic tanks with a temperature of 160°C under 7 bar pressure. These tanks require a vacuum insulation system and internal supports to minimize heat leakage and transfer complex mechanical loads. A 25m³ road tanker's internal supports were proposed, tested using ANSYS software for mechanical and thermal finite element analysis. The growth of LNG liquefaction and regasification capacity in many countries is driven by electricity production, cost reduction, and environmental concerns. In Italy, natural gas is transported via road, but risks such as tank handling and collisions need to be assessed. Italian Firefighters have studied emergency procedures and safety measures for LNG storage and transport in Italy and Europe [15].

Cryogenic pressure vessels are containers used to handle compressible, highly toxic, and high-pressure fluids in various industries. They have high applications but can cause adverse environmental and industry effects when failure occurs. Regulatory bodies regulate design specifications for safety during handling and storage [16].

The "Replacing Coal with Natural Gas" and "Blue Sky Protection Campaign" policies are increasing natural gas consumption. LNG tank containers, suitable for storage and sea and road transport, are becoming a new development in LNG production, supply, storage, and sales. Research on safety, accident simulation, and risk analysis are crucial for ensuring safe operation conditions [17].

The heavy-duty transport sector is focusing on using liquefied natural gas (LNG) to reduce climate change and particle emissions. This presents an opportunity for the biogas market, particularly liquefied biomethane (LBM). A study comparing LBM, LNG, and diesel found that LBM can significantly reduce environmental impact. In Germany, LBM from manure and food waste can reduce climate change by 45-70%. However, LBM's economic viability may be limited due to high production costs and potential economic incentives [18].

This paper discusses the importance of thermal insulation in liquefied natural gas transport tanks. It explores insulation variants, including modern materials like aerogel and fiberglass, and compares them to perlite powder. Heat flux and heat leakage were tested under various gas pressures, and the study aimed to determine the insulation system with low heat leakage and low material and vacuum production costs. The study aims to determine the most suitable insulation for specific applications [19].

The paper discusses the challenge of recovering high nitrogen content in LNG tank cooling, focusing on conventional methods. It suggests full nitrogen replacement and a "BOG+LNG" tank cooling process before commissioning. The results show that nitrogen can be replaced by a "top intake and bottom exhaust" method, and the BOG + LNG cooling process can cool the tank effectively, reducing BOG flow rate and achieving zero BOG emissions. This technology is valuable for new storage tanks and receiving stations with gasification and outward transportation capacity [20].

The study explores the need for a cryogenic explosion-proof camera for LNG carriers, focusing on safety in cryogenic environments below -160°C . The design includes a gap width of 12.5 mm and uses ABAQUS for thermal conductivity analysis. The camera's predicted working time is over 10 hours at warm-start, with 5 hours of pre-warming time required for cold-start. The Pori LNG tank in Finland is being built as the first full containment tank, capable of storing 30,000 m³. The tank faces thermal-mechanical problems due to postulated accidents, such as a major leak event and an external fire. The design is being tested to ensure success [21].

Natural gas vehicles could significantly contribute to transportation needs, but their adoption could impact energy and environmental systems. Factors affecting their adoption include vehicle costs, infrastructure costs, and fuel economics. Liquefied natural gas (LNG) can be competitive as a diesel fuel substitute for heavy-duty vehicles in the US, EU, and China. A methodology for incorporating heavy-duty natural gas vehicles into computable general equilibrium economic modelling was developed. Results showed significant adoption of LNG trucks in the US, with moderately higher natural gas prices and lower oil prices.

Liquid hydrogen (LH₂) is becoming an alternative fuel for future aircraft, necessitating hydrogen tank storage systems for short to long flight durations. This report reviews cryogenic tank materials, structural designs, and insulation systems to develop a lightweight, reusable cryogenic liquid storage tank for LH₂. Insulation systems include foams and multilayer insulation (MLI) systems with vacuum, with potential wall material candidates including monolithic metals, polymer matrix composites, and discontinuously reinforced metal matrix composites. Liner material development trends are also reviewed to minimize hydrogen fuel loss through permeation. Cryogenic rocket propellant tanks store fuel or oxidizer, typically Liquid Hydrogen, at a low temperature of 20 K. Vibration analysis is crucial for estimating frequency levels during engine start and shutdown, causing problems in the tank and its internals. This work uses ANSYS workbench 15.0 for design and modal analysis. This paper discusses the design of cold convertors for storage of liquid oxygen and nitrogen under pressure conditions, analyzing materials used and adhering to industry norms. The procedure for designing nitrogen cold convertors is modified to create a perfect cryogenic vessel, with design calculations and results presented.

3 RESEARCH METHODOLOGY

The methodology for this project follows a structured approach to design, simulate, and optimize an LNG cryogenic tank for heavy commercial vehicle applications using ANSYS. The process involves several key steps, each aimed at ensuring the tank's structural integrity, thermal efficiency, and safety. Fig. 2 is the detailed steps involved in the methodology:

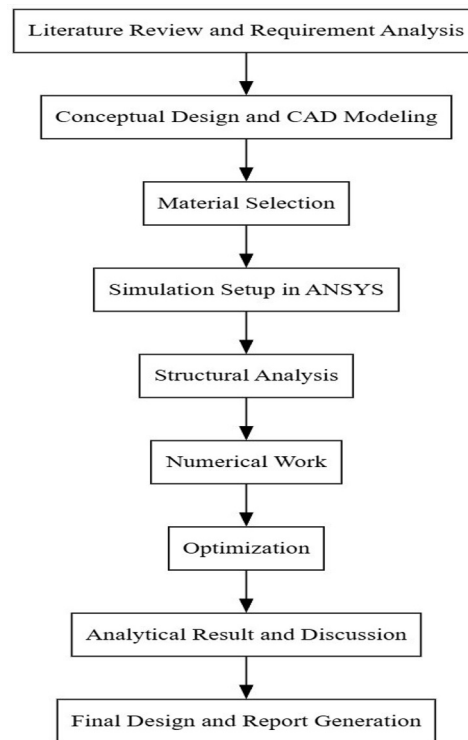


Fig. 2 Methodology Flow Chart

3.1. Literature Review and Requirement Analysis

- Conduct an extensive review of existing LNG cryogenic tank designs, storage requirements, and relevant industry standards.
- Analyze the thermal, structural, and mechanical requirements of LNG storage in commercial vehicles, including constraints related to space, weight, and vehicle dynamics.
- Define design parameters such as pressure ratings, temperature specifications, material properties, and tank dimensions.

3.2. Conceptual Design and CAD Modeling

- Create initial design concepts based on the requirement analysis using CAD software (e.g.,

SolidWorks or AutoCAD).

- Design the cryogenic tank with essential components, such as insulation layers, pressure relief valves, and structural reinforcements, ensuring compatibility with heavy commercial vehicle specifications.
- Develop a detailed 3D model of the LNG cryogenic tank.

3.3. Material Selection

- Select materials that can withstand extreme cryogenic temperatures and high-pressure conditions, such as stainless-steel alloys, aluminum composites, and cryogenic insulation materials.
- Evaluate thermal conductivity, strength, ductility, and thermal expansion properties of selected materials for use in the tank.

3.4. Simulation Setup in ANSYS

- Import the CAD model of the LNG cryogenic tank into ANSYS for further analysis.
- Set up Finite Element Analysis (FEA) to assess the structural integrity of the tank under different loading conditions such as pressure variations, vehicle motion, and external forces.
- Use ANSYS Fluent for Computational Fluid Dynamics (CFD) simulations to model the thermal behavior within the tank and evaluate heat transfer, insulation efficiency, and temperature distribution.
- Incorporate boundary conditions that simulate the dynamic driving conditions and environmental temperature fluctuations.

3.5. Structural Analysis

- Perform stress and strain analysis on the cryogenic tank using ANSYS Mechanical to identify any potential points of failure or weakness under loading conditions.
- Evaluate displacement, von Mises stress, and factor of safety to ensure the tank can handle pressure surges, impact forces, and vibration during vehicle operations.

3.6. Thermal Analysis

- Conduct thermal simulations to assess heat ingress into the LNG tank and temperature gradients across the tank wall.
- Analyze the effectiveness of the insulation system in minimizing LNG boil-off and maintaining the fuel at cryogenic temperatures during transportation.

3.7. Optimization

- Use the simulation results to refine the design for optimal weight, volume, and insulation efficiency while maintaining the required structural integrity and safety.
- Explore design alternatives, such as modifying insulation thickness, tank shape, or material selection to enhance performance and reduce costs.

3.8. Prototype and Testing

- After finalizing the design, create a prototype of the LNG cryogenic tank.
- Conduct physical tests, including pressure tests, thermal performance evaluations, and

vibration resistance tests, to validate the simulation results and ensure compliance with safety standards.

3.9. Final Design and Report Generation

- Based on the analysis, final adjustments to the design will be made.
- Generate a detailed report that includes the simulation results, design modifications, test results, and recommendations for the final LNG cryogenic tank design for commercial vehicle applications.

Proposed Technology

1. ANSYS Simulation Software

Finite Element Analysis (FEA): Used to simulate the structural behavior of the LNG cryogenic tank under various load conditions, such as pressure variations, vibration, and impact forces. FEA helps ensure the tank's structural integrity, safety, and resilience in dynamic vehicle environments.

Computational Fluid Dynamics (CFD): Employed to model thermal performance, including heat transfer, boil-off, and temperature gradients across the tank walls. CFD analysis is crucial for optimizing the insulation system and minimizing heat ingress.

2. 3D CAD Modeling

SolidWorks or **AutoCAD** are used for creating detailed **3D models** of the LNG cryogenic tank. These models include **design components**, **insulation layers**, and **pressure relief systems**, enabling precise visualization and modification of the tank's design.

3. Material Selection

Advanced **materials science** is applied to select **cryogenic-compatible materials** for the tank structure, including **stainless steel alloys** and **composite materials** that can withstand extremely low temperatures and high pressure while maintaining strength and durability.

4. Thermal Insulation Technology

Cryogenic insulation materials, such as **vacuum insulated panels (VIPs)** and **multi-layer insulation (MLI)**, are explored for optimizing the thermal performance of the tank. These materials are key to minimizing **boil-off** and ensuring **fuel stability** during transportation.

5. Pressure Relief and Safety Systems:

The design incorporates advanced **safety technologies**, including **pressure relief valves**, **burst disks**, and **emergency venting systems**, to ensure the tank remains safe under varying pressure conditions during vehicle operation.

4 CONCLUSION

- A comprehensive design for an LNG cryogenic tank tailored for heavy commercial vehicle applications.
- Optimization of weight and size while ensuring safety and efficiency.
- Validation of the design using simulations and real-world testing.
- A comparison of the performance of the proposed LNG tank against traditional fuel tanks in terms of cost, efficiency, and environmental impact.

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