Numerical Simulation and Thermal Optimization of Multi-Layer Insulation (MLI) Systems for Cryogenic Liquid Hydrogen Storage Tanks

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Abstract

Liquid hydrogen (LH_2) is a promising clean energy carrier because of its high energy density and zero carbon emissions during utilization. However, due to its extremely low boiling temperature (20 K), significant heat leakage into storage tanks causes hydrogen boil-off, reducing storage efficiency and increasing operational losses. Multi-Layer Insulation (MLI) is one of the most effective thermal insulation techniques for minimizing heat transfer in cryogenic storage systems. This project aims to numerically investigate the thermal performance of MLI systems applied to liquid hydrogen storage tanks using finite element analysis.

The study focuses on modelling conductive and radiative heat transfer through different MLI configurations. Various parameters including the number of insulation layers, layer spacing, vacuum pressure, and material properties will be analysed to determine their influence on heat leakage and temperature distribution. Numerical simulations will be performed using ANSYS Steady-State Thermal to estimate the overall heat flux and optimize insulation performance.

The expected outcome is an optimized MLI design capable of minimizing heat ingress while maintaining structural feasibility. The numerical results will be validated with published literature to ensure reliability. The findings are expected to contribute toward the development of highly efficient cryogenic storage systems for hydrogen-powered transportation and aerospace applications.

Keywords: Liquid Hydrogen, Cryogenic Storage, Multi-Layer Insulation, Heat Transfer, ANSYS, Thermal Optimization.

CHAPTER 1

INTRODUCTION

1.1 Introduction:

Cryogenic engineering is concerned with the production, storage, transportation and utilization of fluids at extremely low temperatures. Cryogenic temperatures are encountered in applications such as liquefied natural gas, liquid nitrogen, liquid oxygen, liquid helium and liquid hydrogen storage, superconducting systems, aerospace propulsion, medical technologies and advanced energy systems.

Among cryogenic fluids, liquid hydrogen (LH_2) has attracted significant attention because hydrogen has a high specific energy and can be produced from different energy sources. Liquid hydrogen is particularly attractive for applications where high gravimetric energy density and compact storage are important, including aerospace propulsion and emerging hydrogen-energy systems.

The storage of hydrogen in liquid form, however, presents significant thermal-management challenges. Hydrogen must be maintained at approximately 20 K under near-atmospheric pressure, which is far below normal ambient temperatures. Consequently, heat continuously tends to flow from the surroundings into the cryogenic tank. Even a relatively small heat leak can cause evaporation of liquid hydrogen and generate boil-off gas.

The thermal performance of the storage tank therefore depends strongly on the design of its insulation system. Conventional insulation alone may not provide sufficiently low heat transfer for highly efficient long-duration cryogenic storage. Multi-Layer Insulation (MLI) combined with a high-quality vacuum is one of the important approaches used to reduce thermal radiation and overall heat leakage.

MLI consists of multiple thin, low-emissivity reflective layers separated by low-conductivity spacer materials. When installed correctly inside a vacuum environment, these layers significantly reduce radiative heat transfer between the warm outer environment and the cold inner vessel.

However, the thermal performance of MLI does not simply increase indefinitely with the number of layers. Excessive layer density, compression, imperfect vacuum conditions and solid conduction through spacer materials can increase heat transfer. Therefore, identifying an appropriate MLI configuration is an optimization problem.

In this project, numerical simulation is used to investigate the thermal behaviour of an MLI-insulated cryogenic liquid hydrogen storage tank. A computer-aided model is developed and analysed using finite-element-based thermal simulation. The influence of parameters such as MLI layer number, insulation thickness and vacuum conditions is investigated. Temperature distribution, heat flux and total heat leakage are evaluated, followed by an estimation of hydrogen boil-off. The overall objective is to identify an MLI configuration that provides low heat leakage while remaining practically feasible for cryogenic storage applications.

1.2 Background of Cryogenic Liquid Hydrogen Storage:

Hydrogen can be stored in gaseous, liquid or solid-associated forms. For applications requiring large quantities of hydrogen and high storage density, liquefaction provides a significant reduction in storage volume compared with compressed gaseous hydrogen.

Liquid hydrogen has a normal boiling temperature of approximately **20 K**, requiring highly effective thermal insulation. A typical cryogenic storage vessel therefore consists of an inner vessel containing LH_2 and an outer vessel or vacuum jacket surrounding the inner vessel.

A simplified arrangement is:

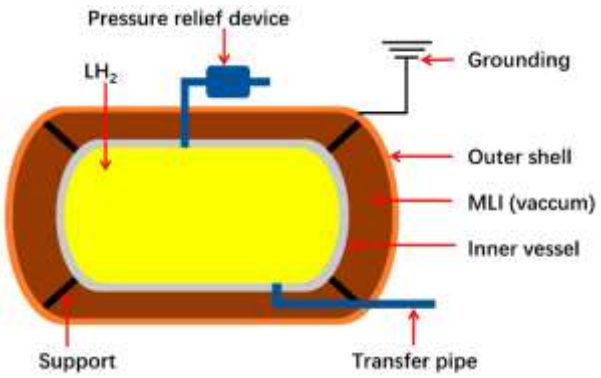


Fig.1.1 Schematic representation of a vacuum-insulated LH_2 storage tank.

The space between the inner and outer vessels is evacuated. The vacuum reduces gas conduction and suppresses convection. MLI placed within this evacuated region further reduces radiation heat transfer.

The basic thermal path can be represented as:

Ambient Environment → Outer Jacket → MLI → Inner Vessel → Liquid Hydrogen

The principal objective of the insulation system is to make the heat transfer along this path as small as possible.

1.3 Properties of Liquid Hydrogen Relevant to the Project:

Liquid hydrogen has several characteristics that make thermal management particularly important.

Important characteristics include:

- Very low boiling temperature
- Low density
- High gravimetric energy content
- High sensitivity to heat input
- Significant volume expansion during vaporization
- Potential for boil-off during storage

Because of the very large temperature difference between the LH_2 and surroundings, even small imperfections in the insulation system can contribute to measurable heat leakage.

The thermal design of an LH_2 tank therefore needs to consider:

1. Tank-wall conduction
2. MLI conduction
3. Radiation between surfaces
4. Residual-gas conduction
5. Thermal bridges through supports
6. Penetrations and instrumentation
7. Vacuum quality

1.4 Need for Cryogenic Thermal Insulation:

Without insulation, the temperature difference between the LH_2 and ambient environment would result in substantial heat transfer.

The consequences include:

- Increased liquid evaporation
- Increased boil-off gas
- Hydrogen loss
- Increased pressure inside the storage tank
- Increased refrigeration requirements
- Reduced storage duration
- Reduced system efficiency

Therefore, a cryogenic storage tank requires an insulation system capable of minimizing heat transfer while maintaining structural and operational reliability.

The ideal insulation system should provide:

- Low effective thermal conductivity
- Low surface emissivity
- Low mass
- Low thickness
- Stable performance under vacuum
- Good mechanical integrity
- Ease of installation
- Long service life

MLI satisfies many of these requirements when properly designed and installed.

1.5 Multi-Layer Insulation (MLI):

MLI is a specialized cryogenic insulation system consisting of multiple reflective layers separated by thin spacer materials.

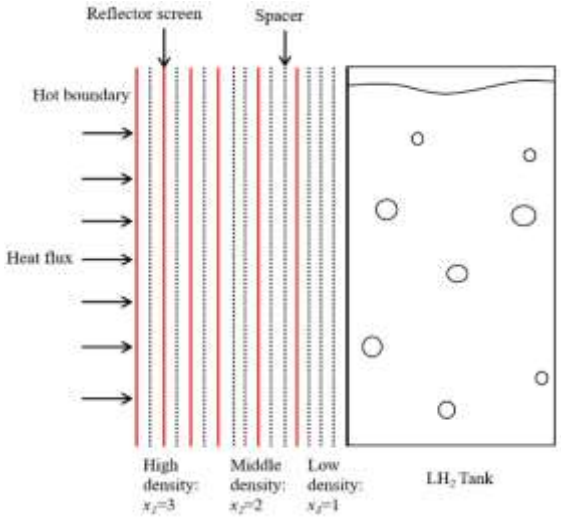


Fig.1.2 Typical MLI arrangement consisting of reflective layers and spacer materials.

The reflective layers generally have low emissivity. They reduce radiation exchange by reflecting thermal radiation away from the cold surface.

The spacer material prevents direct contact between adjacent reflective layers and maintains separation.

Major MLI parameters:

The thermal performance of MLI depends on:

- Number of layers
- Layer density
- Emissivity
- Spacer thickness
- Spacer conductivity
- Vacuum pressure
- Installation quality
- Compression
- Temperature difference

1.6 Heat Transfer Mechanisms in the MLI System:

Three principal heat-transfer mechanisms are considered in the present study.

1.6.1 Conduction:

Heat conduction through solid materials can be represented by Fourier's law:

where:

Q_{cond} = conductive heat-transfer rate, W

k = thermal conductivity, W/m·K

A = cross-sectional area, m²

dT/dx = temperature gradient, K/m

In an MLI system, solid conduction can occur through spacer materials and mechanical supports.

1.6.2 Thermal Radiation:

Radiation becomes particularly important in a high-vacuum cryogenic environment because convection is strongly suppressed.

For simplified radiative exchange:

$Q_{rad}=\varepsilon\sigma A(T_h^4-T_c^4)$

where:

- ε = effective emissivity
- σ = Stefan–Boltzmann constant
- A = radiating area
- T_h= hot-surface temperature
- T_c= cold-surface temperature.

MLI primarily reduces this component by introducing many low-emissivity surfaces.

1.6.3 Residual Gas Conduction:

Even under vacuum, a small quantity of gas may remain inside the insulation space. Depending on the vacuum level, residual-gas conduction can contribute to heat transfer.

Therefore, the vacuum pressure is an important parameter in cryogenic insulation design.

1.7 Heat Leak in Cryogenic Storage Tanks:

Heat leak refers to the unwanted transfer of thermal energy from the surroundings into the cryogenic fluid.

The total heat leak can be represented conceptually as:

$Q_{total}=Q_{cond}+Q_{rad}+Q_{gas}+Q_{support}$

where:

- Q_{cond} = conduction heat transfer
- Q_{rad} = radiation heat transfer
- Q_{gas} = residual-gas conduction
- $Q_{support}$ = heat transfer through structural supports and penetrations.

For an idealized numerical model, some of these terms may be neglected depending on the assumptions. All assumptions must be clearly stated in the report.



Fig.1.3 Heat Leak in Cryogenic Storage Tanks

1.8 Boil-Off of Liquid Hydrogen:

When heat enters the LH_2 tank, part of the liquid may evaporate.

A simplified energy balance can be written as:

where:

$$\dot{m}_{BOG} = Q / h_{fg}$$

$\dot{m}_{BOG}$ = boil-off mass rate, kg/s

Q = heat leak, W

h_{fg} = latent heat of vaporization, J/kg.

Therefore, reducing heat leak directly contributes to reducing the rate of hydrogen evaporation.

This relationship provides an important connection between the thermal simulation results and the practical performance of the storage tank.

CHAPTER 2

PROBLEM STATEMENT

2.1 Background:

Liquid hydrogen (LH_2) is stored at extremely low temperatures of approximately 20 K (−253°C). At this temperature, even a relatively small amount of heat entering the storage tank can cause evaporation of liquid hydrogen, resulting in boil-off losses, pressure rise and reduction in storage efficiency.

Cryogenic storage tanks are therefore designed with highly efficient thermal insulation systems. Among the different insulation technologies, Multi-Layer Insulation (MLI) is widely considered an effective method for reducing heat transfer under high-vacuum conditions. MLI consists of multiple thin reflective layers separated by low-conductivity spacer materials. The insulation system reduces radiative heat transfer and restricts heat transfer through the annular space.

However, the thermal performance of an MLI system depends strongly on several parameters, including:

- Number of insulation layers
- Layer density and spacing
- Reflective foil material
- Spacer material and thickness
- Vacuum pressure
- Surface emissivity
- Temperature difference between the surroundings and stored hydrogen
- Thermal conductivity of the tank and support materials
- Penetrations, supports and piping arrangements

Therefore, determining the optimum MLI configuration for an LH_2 storage tank is an important engineering problem.

2.2 Problem Statement:

The major problem considered in this project is the prediction and minimization of heat leak into a cryogenic liquid hydrogen storage tank through the Multi-Layer Insulation (MLI) system.

The external environment is normally near ambient temperature, approximately 300 K, while the stored liquid hydrogen is maintained near 20 K. This large temperature difference provides a strong driving force for heat transfer from the surroundings toward the cryogenic fluid.

Heat can enter the tank through several mechanisms:

1. Thermal radiation across the vacuum space.
2. Solid conduction through MLI spacers and structural supports.
3. Residual-gas conduction when the vacuum level is insufficient.
4. Heat conduction through piping and instrumentation connections.
5. Thermal bridges created by supports, joints and tank penetrations.

The resulting heat leak causes partial vaporization of liquid hydrogen. The vaporization produces boil-off gas, which may increase tank pressure and reduce the useful storage period.

The problem can therefore be stated as:

To develop a numerical model of a cryogenic liquid hydrogen storage tank incorporating a Multi-Layer Insulation system and to investigate the effect of MLI parameters on temperature distribution, heat flux and total heat leak, with the objective of identifying an optimized insulation configuration that minimizes heat transfer and boil-off losses.

2.3 Heat-Leak Mechanisms in an MLI Cryogenic Tank:

The total heat leak entering the cryogenic tank can be represented approximately as:

$$Q_{total} = Q_{rad} + Q_{cond} + Q_{gas} + Q_{support} + Q_{penetration}$$

Where:

- Q_{total}= total heat leak into the tank, W
- Q_{rad}= radiation heat transfer, W
- Q_{cond}= conduction through insulation, W
- Q_{gas}= residual-gas conduction, W
- $Q_{support}$= conduction through tank supports, W
- $Q_{penetration}$= heat entering through piping and instrumentation, W

For a simplified one-dimensional conduction model:

$$Q_{cond} = \frac{kA(T_h - T_c)}{L}$$

where $k$is thermal conductivity, $A$is heat-transfer area, $T_h$is the hot-side temperature, $T_c$is the cold-side temperature and $L$is the conduction length.

Radiative heat transfer can be expressed approximately as:

$$Q_{rad} = \frac{\sigma A\left(T_h^4 - T_c^4\right)}{\left(\frac{1}{\varepsilon_h}\right) + \left(\frac{1}{\varepsilon_c}\right) - 1}$$

where:

- σ= Stefan–Boltzmann constant
- A= radiating surface area
- ε_h= emissivity of the hot surface
- ε_c= emissivity of the cold surface

These mechanisms are incorporated into the numerical model to evaluate the thermal performance of the proposed MLI system.

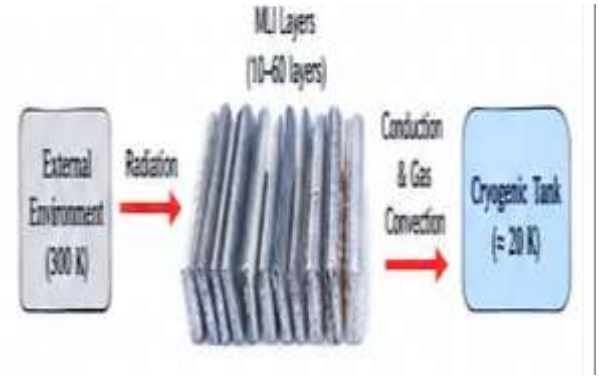


Fig.2.1 Heat transfer paths in an MLI System



Fig.2.2 Effects of MLI optimization on heat leaks

2.4 Research Problem:

The research problem addressed in this project can be summarized as follows:

How can the MLI configuration of a cryogenic liquid hydrogen storage tank be numerically modelled and thermally optimized to minimize heat leak and corresponding hydrogen boil-off while maintaining a practical and efficient tank design?

The study particularly investigates the relationship between:

- MLI layer number and heat leak
- MLI thickness and heat leak
- Vacuum pressure and heat transfer
- Material properties and thermal performance
- Temperature distribution across the insulation
- Heat flux through the tank wall
- Total heat leak and hydrogen boil-off rate

CHAPTER 3

AIM AND OBJECTIVES

3.1 Aim of the Study:

The primary aim of this project is to develop a numerical model and thermally optimize a Multi-Layer Insulation (MLI) system for a cryogenic liquid hydrogen (LH_2) storage tank in order to minimize heat leak and associated hydrogen boil-off losses.

The study focuses on developing a suitable cryogenic storage-tank geometry, incorporating an MLI system, simulating the thermal behavior under cryogenic operating conditions and evaluating the effects of important MLI parameters such as layer number, layer spacing, emissivity, spacer material and vacuum pressure.

The numerical analysis will be carried out using an ANSYS-based thermal simulation approach. The simulation results will be used to determine temperature distribution, heat flux and total heat leak through the insulation system. Based on these results, the MLI configuration will be optimized to obtain minimum thermal losses while maintaining a practical and efficient cryogenic storage-tank design.

The overall aim can therefore be expressed as:

To numerically investigate and thermally optimize the Multi-Layer Insulation system of a cryogenic liquid hydrogen storage tank for minimum heat leak and boil-off rate, thereby improving storage efficiency, thermal performance and storage duration.

3.2 General Objectives:

The general objectives of the present study are:

1. To develop a suitable 3D CAD model of a cryogenic liquid hydrogen storage tank.
2. To incorporate a Multi-Layer Insulation (MLI) system around the inner LH_2 vessel.
3. To develop a numerical thermal model for analysing heat transfer through the tank insulation.
4. To investigate the major heat-transfer mechanisms associated with MLI systems.
5. To determine the temperature distribution and heat flux across the tank and insulation.
6. To calculate the total heat leak entering the cryogenic storage tank.
7. To estimate the corresponding liquid hydrogen boil-off rate.
8. To investigate the influence of MLI design parameters on thermal performance.
9. To identify the optimum MLI configuration for minimum heat leak.
10. To validate the numerical results using analytical correlations and available published cryogenic data.

3.3 Specific Objectives:

The specific objectives of the project are divided into modelling, simulation, analysis, optimization, and validation stages.

3.3.1 CAD Modelling Objective:

To develop an accurate CAD model of a cylindrical cryogenic liquid hydrogen storage tank consisting of:

- Inner LH_2 storage vessel
- Tank wall
- MLI layers

- Vacuum space
- Outer protective vessel
- Appropriate support/structural regions

The geometry will be developed using suitable CAD software such as **SolidWorks, CATIA, or AutoCAD**, depending on the modelling requirements.

3.3.2 Material Selection Objective:

To identify appropriate materials for the cryogenic tank and insulation system based on:

- Thermal conductivity
- Density
- Specific heat
- Emissivity
- Mechanical strength
- Cryogenic compatibility
- Temperature-dependent properties

The selected materials should be capable of maintaining structural and thermal performance at cryogenic temperatures.

3.3.3 MLI Configuration Objective:

To investigate the effect of different MLI configurations by varying parameters such as:

- Number of MLI layers
- MLI thickness
- Layer spacing
- Layer density
- Effective thermal conductivity
- Surface emissivity
- Vacuum pressure

The purpose is to determine how these parameters influence the overall thermal resistance of the storage system.

3.3.4 ANSYS Simulation Objective:

To perform numerical thermal analysis using ANSYS by defining:

- Geometry
- Material properties
- Mesh
- Initial conditions
- Boundary conditions
- Thermal loads

- Solver settings
- Convergence criteria

The simulation will be performed for different MLI configurations.

3.3.5 Temperature Distribution Objective:

To determine the temperature distribution through the cryogenic tank system and obtain temperature contours at different locations.

The analysis will identify:

- Inner tank temperature
- MLI temperature distribution
- Outer tank temperature
- Temperature gradient
- Maximum and minimum temperature regions

3.3.6 Heat Leak Objective:

To calculate the heat transfer from the ambient environment into the LH_2 tank.

The heat leak will be evaluated using the simulated:

- Heat flux
- Temperature difference
- Thermal resistance
- Effective thermal conductivity
- Insulation characteristics

A lower heat leak indicates improved insulation performance.

3.3.7 Boil-Off Objective:

To estimate the hydrogen boil-off resulting from the heat entering the storage tank.

The relationship between heat leak and boil-off will be evaluated using the latent heat of vaporization of liquid hydrogen:

$$\dot{m}_{BO} = \frac{\dot{Q}}{h_{fg}}$$

Where:

$\dot{m}_{BO}$ = hydrogen boil-off rate (kg/s)
$\dot{Q}$ = heat leak into the tank (W)
h_{fg} = latent heat of vaporization of LH_2 (J/kg)

This analysis will help quantify the practical importance of reducing heat leak.

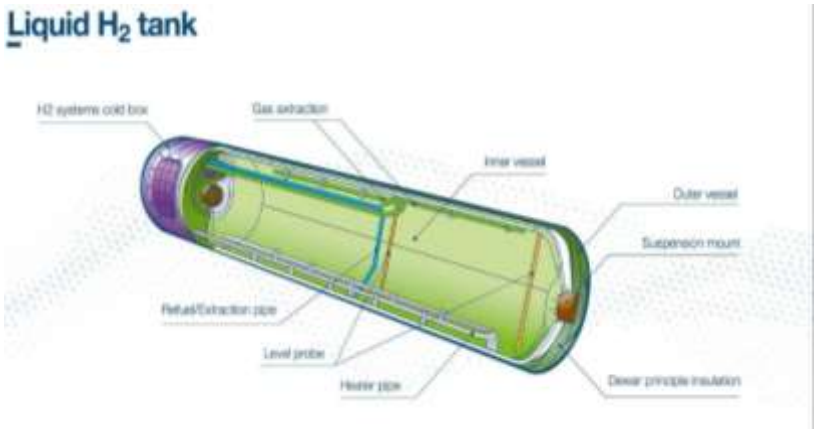


Fig.3.1 Cryogenic LH_2 Storage Tank with Multi-Layer Insulation System

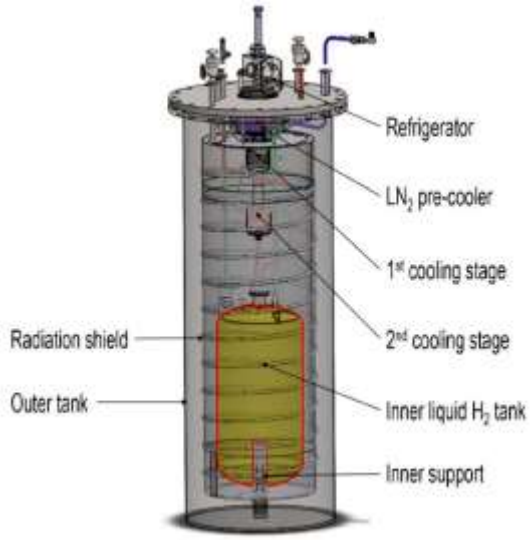


Fig. 3.2 Major Parameters Considered for MLI Optimization.

CHAPTER 4

LITERATURE REVIEW

Cryogenic liquid hydrogen (LH_2) storage requires highly efficient thermal insulation because LH_2 is stored at approximately 20 K (−253°C). The large temperature difference between the ambient surroundings and the stored hydrogen causes heat to enter the storage vessel. This heat input can lead to evaporation of LH_2, resulting in boil-off losses and pressure increase. Therefore, reducing heat leak is a major requirement in the design of efficient LH_2 storage tanks. Recent reviews identify multilayer insulation (MLI), composite insulation and vapor-cooled shields as important passive thermal-protection technologies for LH_2 storage systems.

Ratnakar, Sun and Balakotaiah (2023) reviewed the effective thermal conductivity of insulation materials used for cryogenic liquid hydrogen storage tanks. Their study considered different insulation systems, including powders, foams, fibrous materials and multi-layer insulation. The authors emphasized that accurate prediction of effective thermal conductivity is essential for estimating heat leak and hydrogen boil-off. They also developed a physics-based correlation considering temperature, pressure, interstitial gas and structural properties of insulation. The study showed that heat transfer through cryogenic insulation can be considered in terms of solid conduction, radiation and gas conduction. This work provides an important theoretical basis for selecting thermal properties for the numerical simulation of LH_2 storage tanks.

Stochl and Knoll (1991) experimentally investigated the thermal performance of a liquid hydrogen tank equipped with a multi-layer insulation system. Their experimental tank used 34 MLI layers, consisting of aluminized Mylar radiation shields and silk-net spacer layers. The researchers investigated different warm-boundary temperatures and measured the resulting heat transfer into the LH_2 tank.

Their study also considered heat leakage through structural supports, plumbing and instrumentation. They reported that non-insulation heat leaks accounted for approximately 13–17% of the total heat input in the tested configuration. This research is particularly important for the present project because it demonstrates that thermal bridges must be considered in addition to the MLI blanket itself.

Kang, An and Lee (2024) investigated numerical modelling and optimization of thermal insulation for liquid hydrogen storage tanks. Their work developed a numerical model capable of calculating heat flux while considering the physical geometry of the storage tank. They investigated insulation thickness and combinations of solid insulation, MLI and vapor-cooled shields. Their results demonstrated that optimization of insulation configuration can significantly reduce insulation requirements while maintaining thermal performance. The authors reported substantial reductions in MLI layers when a vapor-cooled shield was incorporated under suitable vacuum conditions. This study supports the use of numerical simulation and optimization techniques for improving the thermal performance of LH_2 storage tanks.

Chen, Lv, Shang, Zhang, Chen and Hou (2024) presented a comprehensive review of strategies for improving the thermal insulation performance of liquid hydrogen tanks using MLI structures. The authors discussed the effects of MLI material, layer density, layer arrangement, vacuum conditions and vapor-cooled-shield position. Their review highlighted that simply increasing the number of insulation layers does not necessarily provide the best thermal performance because excessive layer density can increase solid conduction. The authors therefore emphasized optimization of MLI structure and layer density. This research is directly relevant to the present project because the proposed study aims to identify an optimum MLI configuration rather than simply maximizing the number of insulation layers.

Knoll, Stochl and Sanabria (1991) reviewed candidate MLI systems for liquid-hydrogen tankage intended for space applications. Their work examined different insulation arrangements and materials for cryogenic LH_2 storage and emphasized the importance of achieving high thermal resistance while maintaining low mass and practical structural characteristics. The study provided early engineering guidance for the selection and arrangement of MLI systems for LH_2 tanks. Although the study was conducted several decades ago, it remains relevant because the fundamental mechanisms of cryogenic insulation—radiation, conduction, vacuum effects and thermal bridging—continue to influence modern tank design.

Recent numerical and thermal-insulation research has increasingly focused on combining MLI with other thermal-management technologies and developing models capable of predicting heat flux under different operating conditions. Kang, An and Lee (2024), for example, considered physical tank geometry, vacuum pressure, MLI and vapor-cooled shields in their numerical optimization study. Their results demonstrate that numerical modelling can be used to investigate insulation thickness and configuration before fabrication. Such an approach reduces the need for repeated physical prototypes and allows multiple design cases to be compared systematically. Therefore, numerical simulation using tools such as ANSYS is suitable for evaluating temperature distribution, heat flux and heat leak in the proposed LH_2 storage tank model.

From the above literature, it is evident that MLI layer number, layer density, spacer material, surface emissivity, vacuum pressure, temperature conditions and thermal bridges strongly influence the heat leak of LH_2 storage tanks. However, further work is required to integrate these parameters into a systematic numerical optimization framework. Therefore, the present project, “Numerical Simulation and Thermal Optimization of Multi-Layer Insulation (MLI) Systems for Cryogenic Liquid Hydrogen Storage Tanks,” proposes to develop a CAD model and ANSYS thermal model, investigate different MLI configurations,determine temperature distribution and heat flux, calculate total heat leak and estimated LH_2 boil-off, and identify an optimized MLI configuration through numerical comparison and validation. This approach directly builds on the experimental and modelling findings reported in the literature.

CHAPTER 5

METHODOLOGY

5.1 Introduction

The present project, "Numerical Simulation and Thermal Optimization of MultiLayer Insulation (MLI) Systems for Cryogenic Liquid Hydrogen Storage Tanks," focuses on developing a numerical model to investigate heat transfer through an MLI-insulated liquid hydrogen storage tank. The methodology consists of CAD modelling, MLI configuration development, material-property definition, ANSYS meshing, thermal boundary conditions, numerical simulation, heat-leak calculation, LH_2 boil-off estimation, optimization and validation.

5.2 Overall Methodology:

The work begins with literature review and definition of tank geometry and operating conditions. A three-dimensional CAD model is developed, followed by MLI configuration and assignment of thermal properties. The model is imported into ANSYS, meshed and checked for mesh independence. Cryogenic and ambient boundary conditions are applied and the thermal model is solved. Temperature distribution, heat flux and total heat leak are obtained, followed by LH_2 boil-off estimation. Several MLI configurations are compared and the best configuration is selected through thermal optimization.

The methodology adopted for the project follows the sequence:

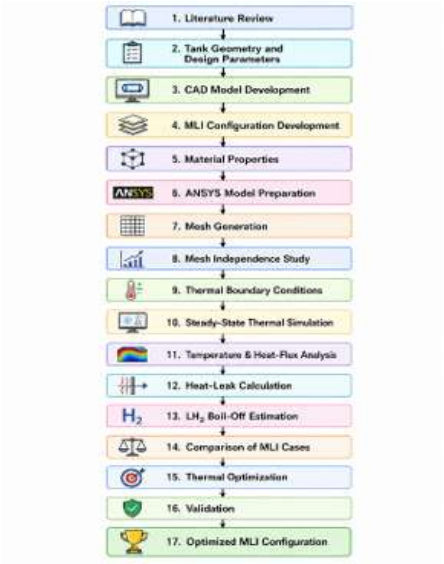


Fig. 5.1 Overall Research Methodology

5.3 Project Inputs and Outputs:

The principal inputs are tank dimensions, material properties, MLI layer number, layer density, spacer properties, surface emissivity, vacuum condition and operating temperatures. The principal outputs are temperature distribution, heat-flux distribution, total heat leak and estimated LH_2 boil-off rate.

5.4 CAD Model Development:

The cryogenic storage tank is modelled using SolidWorks, CATIA, AutoCAD or ANSYS Space Claim/Design Modeler. The geometry contains an inner vessel for LH_2, an MLI/vacuum region, an outer vacuum jacket and representative supports or penetrations where required.

The model is created with dimensions suitable for numerical analysis and is simplified where necessary without changing the dominant thermal paths.

5.5 MLI Configuration Development:

The MLI system consists of multiple low-emissivity reflective layers separated by low-conductivity spacer material. Important design variables are the number of layers (N), total MLI thickness, layer density, spacer material,

surface emissivity and vacuum pressure. Layer density may be expressed as N^d = N/tMLI. The model can represent individual layers for a detailed study or an equivalent-property region when computational efficiency is required.

5.6 Material Properties:

The inner and outer vessels may be represented by stainless steel or an aluminium alloy, while the reflective insulation may be modelled using an aluminized polymer film. Low-conductivity spacer materials such as Dacron or glass tissue may be considered. Thermal conductivity, density, specific heat and emissivity should be entered as temperature-dependent properties wherever reliable data are available.

5.7 Heat-Transfer Mechanisms in MLI:

Heat transfer through MLI is mainly associated with radiation between reflective layers, solid conduction through spacers and structural paths, and residual-gas conduction when the vacuum is imperfect. The total heat leak may be considered as $Q_{total} = Q_{rad} + Q_{cond} + Q_{gas} + Q_{bridge}$.

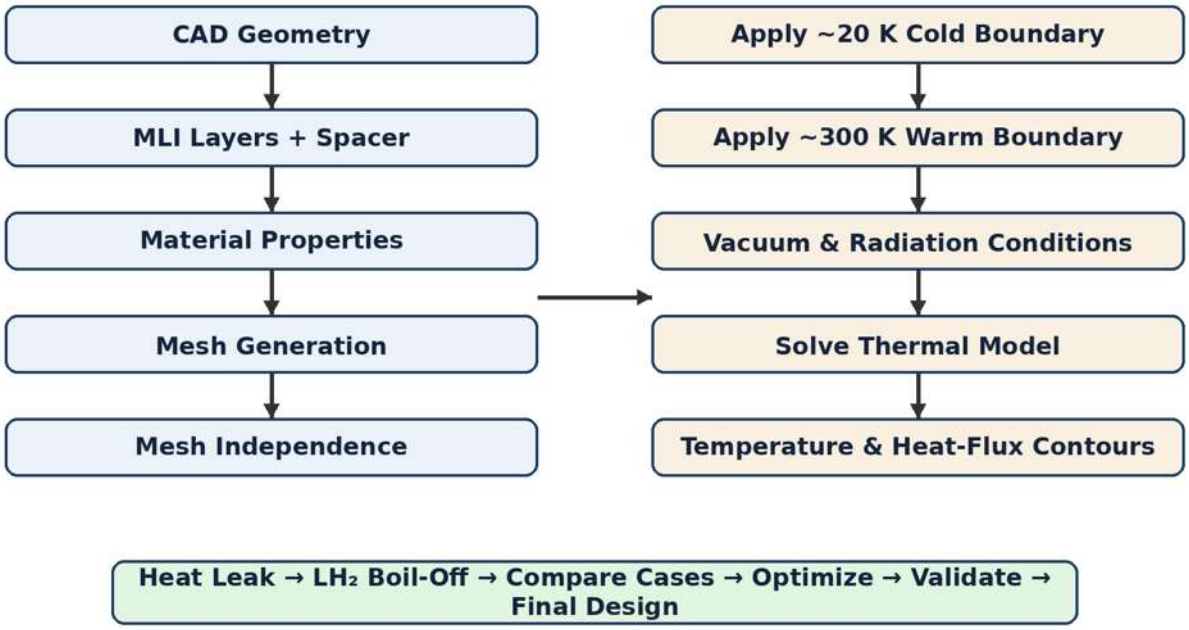


Fig. 5.2 ANSYS thermal simulation and optimization workflow.

5.8 Meshing and Mesh Independence:

After geometry preparation, the model is discretized into finite elements. A sufficiently refined mesh is required near the inner vessel, MLI interfaces, supports and other regions with high temperature gradients. A mesh-independence study is carried out by comparing heat-leak results for coarse, medium and fine meshes. The final mesh is selected when further refinement produces only a small change in the principal result.

5.9 Thermal Boundary Conditions:

A representative model uses a cold-side temperature close to the LH_2 saturation condition, approximately 20 K, and an ambient-side temperature of about 293–300 K. The MLI region is assigned the selected vacuum condition and appropriate surface emissivity. Structural supports and penetrations are included as thermal-conduction paths when they are part of the chosen model.

Boundary	Condition	Representative value
Inner vessel / LH_2 side	Temperature	≈ 20 K
Outer jacket	Temperature	≈ 293–300 K
MLI space	Vacuum pressure	Project-selected value
Reflective surfaces	Emissivity	Project-selected value
Supports / penetrations	Conduction	Included where applicable

Table 5.1Thermal Boundary Conditions.

5.10 ANSYS Thermal Simulation:

The completed geometry, material properties, mesh and boundary conditions are solved using a steady-state thermal analysis. The main results are temperature contours, temperature gradients, total heat flux, directional heat flux and total heat-transfer rate. These results are used to determine the heat leak through the tank insulation system.

5.11 Heat-Leak Calculation:

For an equivalent insulation region, a preliminary analytical estimate can be written $Q_{leak} = k_{eff} A(Tw - Tc)/L$ where k_{eff} is effective thermal conductivity, A is heat-transfer area, Tw and Tc are warm- and cold-side temperatures, and L is insulation thickness. The ANSYS solution is then used to obtain the corresponding numerical heat-transfer rate.

5.12 LH_2 Boil-Off Estimation:

The estimated hydrogen boil-off rate is obtained from $\dot{m}_{BO} = Q_{leak}/h_{fg}$, where h_{fg} is the latent heat of vaporization of liquid hydrogen. Therefore, reducing heat leak directly reduces hydrogen evaporation and improves storage duration.

5.13 Simulation Cases:

Five simulation cases are proposed to study the effect of MLI configuration. Case 1 represents a low-layer baseline; Case 2 uses a medium layer count; Case 3 uses a high layer count; Case 4 investigates an optimized or variable layer density; and Case 5 represents the final optimized configuration combined with an improved vacuum condition. Exact layer counts and vacuum pressures should be replaced by the values adopted in the final ANSYS model.

Case	MLI configuration	Main variable	Purpose
1	Low-layer MLI	Layer number	Baseline
2	Medium-layer MLI	Layer number	Intermediate performance
3	High-layer MLI	Layer number	High insulation density
4	Optimized / variable-density MLI	Layer spacing	Optimization study
5	Final optimized MLI	Combined parameters	Best thermal performance

Table 5.2 Simulation Cases.

5.14 Thermal Optimization:

The optimization objective is to minimize total heat leak while maintaining a practical insulation thickness, layer density and vacuum condition. The principal objective can be expressed as min (Q_{leak}). The results are compared using maximum and minimum temperature, heat flux, total heat leak, estimated boil-off rate, MLI thickness and layer density.

5.15 Validation:

Validation is performed by comparing the numerical heat-leak result with an analytical calculation and/or published experimental or numerical data. Percentage error may be calculated as % Error = $|Q_{sim} - Q_{ref}|/Q_{ref} \times 100$. Agreement within an acceptable engineering range provides confidence in the numerical model.

5.16 Final Methodology:

The complete workflow is: Literature Review → Tank Geometry → CAD Model → MLI Configuration → Material Properties → ANSYS Meshing → Mesh Independence → Boundary Conditions → Thermal Simulation → Temperature and Heat Flux → Heat Leak → LH_2 Boil-Off → MLI Case Comparison → Optimization → Validation → Final Optimized Design.

CHAPTER 6

MATERIALS AND COMPONENTS SELECTION

6.1 Introduction:

The selection of suitable materials and components is an important stage in the design and numerical simulation of a cryogenic liquid hydrogen storage tank. The selected materials must withstand extremely low temperatures, thermal gradients, vacuum conditions and mechanical loads while minimizing heat transfer into the stored liquid hydrogen.

For the present project, the material and component selection is mainly focused on the cryogenic storage tank, Multi-Layer Insulation (MLI), vacuum space, structural supports and ANSYS simulation model.

The major components considered are:

1. Inner cryogenic vessel
2. Outer vessel
3. Multi-Layer Insulation (MLI)
4. Reflective foil
5. Spacer material
6. Vacuum insulation space
7. Structural supports
8. Liquid hydrogen
9. Thermal interfaces
10. CAD and ANSYS simulation components

6.2 Material Selection Criteria:

The materials are selected based on:

- Good mechanical strength at cryogenic temperatures.
- Good fracture toughness at low temperature.
- Low thermal conductivity where required.
- Resistance to thermal cycling.

- Low outgassing under vacuum.
- Compatibility with hydrogen service.
- Suitable surface emissivity.
- Corrosion resistance.
- Low thermal expansion where appropriate.
- Availability and manufacturability.

For the thermal simulation, particular attention is given to thermal conductivity, density, specific heat and surface emissivity.

6.3 Inner Cryogenic Vessel:

The inner vessel is the primary container that stores liquid hydrogen. Austenitic stainless steel, such as SS 304L, is considered for the inner vessel because of its suitable cryogenic mechanical properties and good toughness at low temperatures.

Functions:

- Stores liquid hydrogen.
- Provides the cold boundary of the thermal model.
- Withstands internal pressure.
- Transfers heat between the MLI system and stored fluid.

Important properties:

- Density
- Thermal conductivity
- Specific heat
- Young's modulus
- Poisson's ratio
- Thermal expansion coefficient

For the ANSYS model, temperature-dependent properties should preferably be used.

6.4 Outer Vessel:

The outer vessel surrounds the insulation and provides the external boundary of the storage system. Stainless steel is considered because of its strength, durability and suitability for vacuum service.



Fig. 6.1 Outer Vessel

Functions:

- Encloses the MLI system.
- Maintains the vacuum insulation space.
- Protects the inner vessel and MLI.
- Provides mechanical support.
- Represents the warm boundary of the thermal system.

The outer surface can be subjected to an ambient temperature or an appropriate convection/radiation boundary condition in ANSYS.

6.5 Multi-Layer Insulation (MLI):

MLI is the principal insulation system investigated in this project. It consists of multiple reflective layers separated by spacer materials.

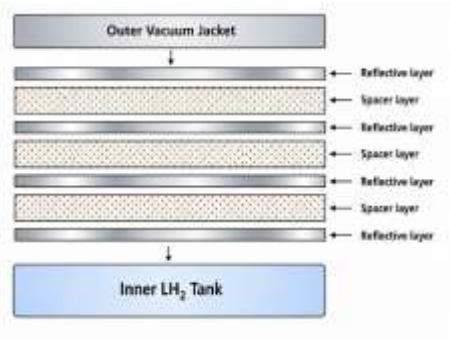


Fig. 6.2 Multi-Layer Insulation

A typical arrangement is:

Reflective layer → Spacer → Reflective layer → Spacer → Reflective layer

This arrangement is repeated to obtain the required number of insulation layers.

Main function:

MLI reduces heat transfer primarily by reducing thermal radiation between the warm outer vessel and the cold inner vessel.

The effectiveness of MLI depends on:

- Number of layers
- Layer density
- Surface emissivity
- Spacer thickness
- Vacuum pressure
- Compression
- Installation quality

6.6 Reflective Foil:

An aluminium-coated polymer film, such as aluminized Mylar, is considered as the reflective material.

The reflective film provides a low-emissivity surface that reduces radiative heat exchange between adjacent layers.

Functions:

- Reflects thermal radiation.
- Reduces radiative heat transfer.
- Provides a lightweight insulation layer.
- Forms the primary radiation barrier in MLI.

Important parameters:

Property	Importance
Emissivity	Controls radiation heat transfer
Thickness	Influences layer arrangement
Thermal conductivity	Influences solid conduction
Density	Influences overall mass
Surface condition	Influences radiation performance

Table 6.1 Property and importance

6.7 Spacer Material:

Spacer materials are placed between adjacent reflective layers. A polyester/Dacron-type material can be considered for this purpose.

Functions:

- Maintains separation between reflective films.
- Prevents direct contact between layers.
- Reduces solid conduction.
- Provides mechanical stability.
- Maintains the required layer spacing.

The spacer thickness and compression are important because excessive compression can increase solid conduction and reduce MLI performance.



Fig. 6.3 Spacer Material

6.8 Vacuum Insulation Space:

The space between the inner and outer vessels is maintained under high vacuum in a practical MLI storage system.

The vacuum reduces:

- Gas conduction.
- Natural convection.
- Heat transfer through residual gases.

The effectiveness of MLI is strongly dependent on maintaining an appropriate vacuum condition.

For the numerical model, the vacuum region can be represented using appropriate thermal assumptions or residual-gas conduction models depending on the level of simulation detail.

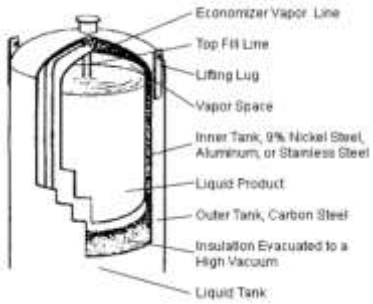


Fig. 6.4 Vacuum Insulation Space

6.9 Structural Supports:

Structural supports maintain the position of the inner tank inside the outer vessel.

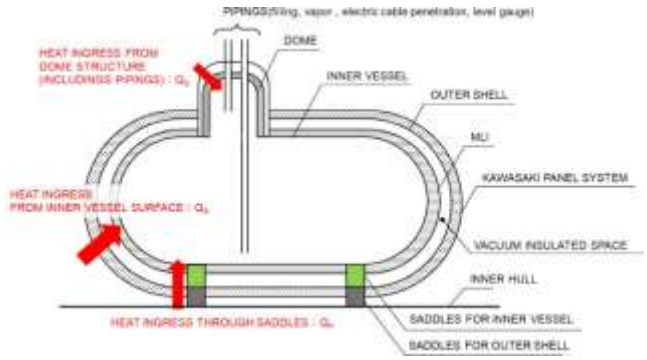


Fig. 6.5 Structural Supports

However, structural supports can act as thermal bridges, transferring heat from the warm outer vessel toward the cold inner vessel.

Therefore, support design is important for minimizing parasitic heat leak.

Functions:

- Support the inner vessel.
- Maintain alignment.
- Carry mechanical loads.
- Reduce movement and vibration.

- Minimize conductive heat leak.

6.10 Liquid Hydrogen:

Liquid hydrogen is the working cryogenic fluid considered in the project. It is stored at approximately 20 K under atmospheric-pressure saturation conditions, with the exact temperature depending on pressure.



Fig. 6.6 Liquid Hydrogen Tanker

Important thermophysical properties include:

- Density
- Specific heat
- Thermal conductivity
- Saturation temperature
- Latent heat of vaporization
- Pressure-temperature relationship

These properties are required for heat-leak and boil-off calculations.

6.11 Thermal Interfaces:

Thermal interfaces are defined between adjoining components in the numerical model.

Examples include:

- Inner vessel–MLI interface
- MLI–outer vessel interface
- Support–inner vessel interface
- Support–outer vessel interface

Appropriate thermal contact assumptions are important because imperfect contact can influence the calculated heat transfer.

6.12 Materials and Components Used:

Sl. No.	Component	Selected/Considered Material	Function
1	Inner vessel	SS 304L	LH_2 storage
2	Outer vessel	Stainless steel	Vacuum enclosure
3	Reflective layer	Aluminium-coated Mylar/polymer	Radiation reduction
4	Spacer	Dacron/polyester	Layer separation
5	MLI	Reflective film + spacer	Thermal insulation
6	Vacuum region	High-vacuum space	Reduces gas conduction
7	Structural supports	Low-conductivity structural material	Mechanical support
8	Working fluid	Liquid hydrogen	Cryogenic fluid
9	Thermal interfaces	Appropriate contact definition	Heat-transfer representation

Table 6.2 Material and Component Selection

6.13 Material Properties Required in ANSYS:

The following properties are required for the thermal simulation

Property	Symbol	Unit
Density	ρ	kg/m^3
Thermal conductivity	k	W/m·K
Specific heat	Cp	J/kg·K
Surface emissivity	ε	Dimensionless
Thermal expansion coefficient	α	1/K
Contact conductance	hc	$W/m^2 \cdot K$

Table 6.3 Important Material Properties

Where reliable cryogenic data are available, temperature-dependent properties should be entered into ANSYS rather than assuming constant room-temperature properties.

6.14 Components Used in CAD and ANSYS:

The numerical workflow uses the following major software/model components:

Component	Application
CAD software	Tank geometry development
ANSYS Workbench	Simulation environment
ANSYS Space Claim/Design Modeler	Geometry preparation
ANSYS Engineering Data	Material definition

ANSYS Meshing	Finite-element mesh generation
ANSYS Mechanical	Thermal simulation
Post-Processor	Contours and result extraction

Table 6.4 Components Used in CAD and ANSYS

CHAPTER 7

DESIGN AND DEVELOPMENT

7.1 Introduction:

The design and development stage converts the proposed methodology into a numerical model of a cryogenic liquid hydrogen (LH_2) storage tank. The objective is to develop a double-wall tank with an inner vessel, vacuum space, multi-layer insulation (MLI) and outer vacuum jacket, and to prepare the geometry for ANSYS thermal analysis.

7.2 Design Requirements:

The main design requirements are low heat leak, adequate vacuum clearance, low-emissivity radiation shields, minimum thermal bridging and geometry suitable for finite-element analysis. The model is designed to represent heat transfer from the ambient environment to LH_2 maintained near 20 K.

7.3 Tank Configuration:

The proposed tank uses a cylindrical double-wall arrangement. LH_2 is stored inside the inner vessel; the MLI occupies the vacuum space; and the outer jacket forms the warm boundary and vacuum enclosure. Rounded ends may be used to provide a realistic pressure-vessel geometry.



Fig. 7.1 CAD design schematic of the MLI-insulated LH_2 storage tank.

7.4 CAD Geometry Development:

The three-dimensional geometry can be developed using SolidWorks, CATIA, AutoCAD or ANSYS Space Claim/Design Modeler. A representative cylindrical geometry may use a length of 1000 mm and outer diameter of 500 mm as initial project assumptions. Final dimensions should be replaced by the approved CAD model.

7.5 Major CAD Components:

The major components are: (1) inner LH_2 vessel, (2) MLI region, (3) vacuum space, (4) outer vacuum jacket, and (5) supports or penetrations where required. These components define the principal thermal paths.

7.6 MLI Design:

The MLI contains alternating low-emissivity reflective layers and low-conductivity spacers. Important variables are layer number, total MLI thickness, layer density, spacer conductivity, surface emissivity and vacuum pressure. Layer density is defined by $N^d = N/t$ MLI.

7.7 CAD-to-ANSYS Preparation:

After CAD completion, unnecessary geometric details are removed while retaining dominant thermal paths. Interfaces are checked and the final model is exported to ANSYS for material assignment, meshing and thermal analysis.

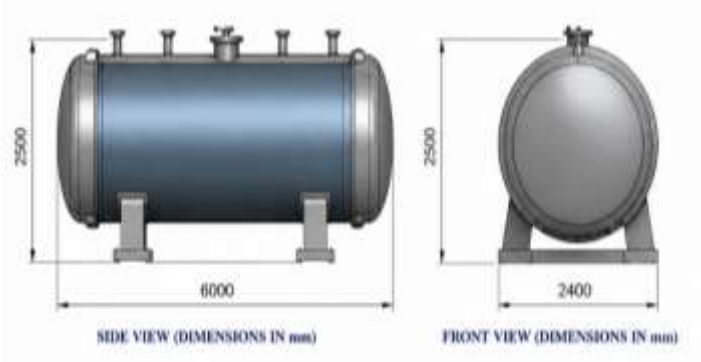


Fig. 7.2 CAD design schematic of the tanker in side view and front view

7.8 ANSYS Geometry and Analysis Model:

The CAD model is imported into ANSYS Space Claim or Design Modeler. The thermal model contains the inner vessel, MLI/vacuum region and outer jacket. Supports and penetrations may be included when their thermal-bridge effect is part of the study.

7.9 Material Definition:

Stainless steel or aluminium alloy may be assigned to the vessel and jacket. Aluminized polymer film is used as a representative reflective layer and Dacron or glass tissue may be considered as spacer material. Temperature-dependent thermal conductivity, density, specific heat and emissivity should be used whenever reliable data are available.

7.10 Meshing Strategy:

The geometry is discretized into finite elements. Finer elements are used near the inner wall, MLI interfaces and thermal bridges. A mesh-independence study compares heat-leak results for progressively refined meshes.

7.11 Mesh Quality:

The final mesh should provide stable heat-leak results with acceptable computational cost. The actual element size, element count and quality statistics obtained from ANSYS should be inserted in the final project report.

7.12 Thermal Boundary Conditions:

A representative model uses approximately 20 K at the LH_2/inner-vessel side and approximately 293–300 K at the ambient-side outer jacket. The MLI region is associated with the selected vacuum condition and surface emissivity. Supports are modelled as conduction paths where applicable.

7.13 ANSYS Thermal Analysis:

A steady-state thermal analysis is performed after assigning materials, mesh and boundary conditions. The solver provides temperature distribution, temperature gradient, total heat flux, directional heat flux and total heat-transfer rate.

7.14 Heat-Transfer Model:

For preliminary comparison, conduction through an equivalent insulation region can be expressed as $Q = k_{eff} A (T_w - Tc)/L$. The detailed numerical model combines radiation, spacer conduction, residual-gas conduction and thermal-bridge effects.

7.15 Design Outputs:

The principal outputs are maximum and minimum temperature, temperature gradient, heat flux, total heat leak and estimated LH_2 boil-off. These outputs are used to compare the MLI configurations.



Fig. 7.3 Geometry (3D model)



Fig. 7.4 Temperature contour

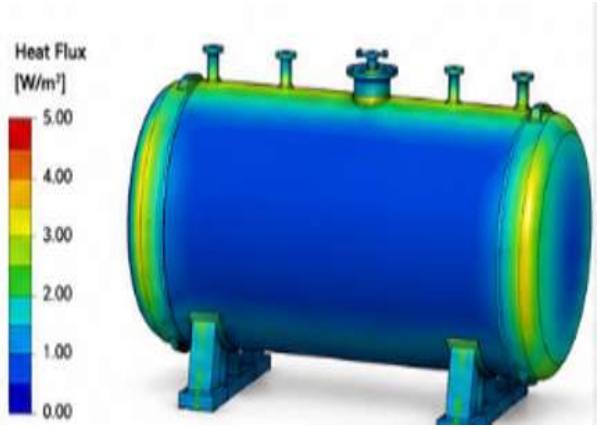


Fig. 7.5 Heat flux contour

7.16 Simulation Cases:

Five cases are proposed: Case 1 low-layer MLI, Case 2 medium-layer MLI, Case 3 high-layer MLI, Case 4 variable/optimized layer density, and Case 5 optimized MLI combined with improved vacuum. Exact layer counts and vacuum pressures should be replaced by the final simulation values.

CHAPTER 8

EXPERIMENTAL SETUP

8.1 Introduction:

The experimental setup is designed to evaluate the thermal performance of a Multi-Layer Insulation (MLI) system for cryogenic liquid hydrogen (LH_2) storage. Since the present project mainly focuses on numerical simulation and optimization, the experimental arrangement is proposed as a validation system for the ANSYS simulation results.

The setup consists of a double-wall cryogenic storage vessel, MLI layers, vacuum jacket, vacuum pumping system, temperature sensors, pressure sensors and a data acquisition system. The inner vessel contains LH_2, while the evacuated annular space containing MLI minimizes heat transfer from the surroundings.

8.2 Schematic Diagram:

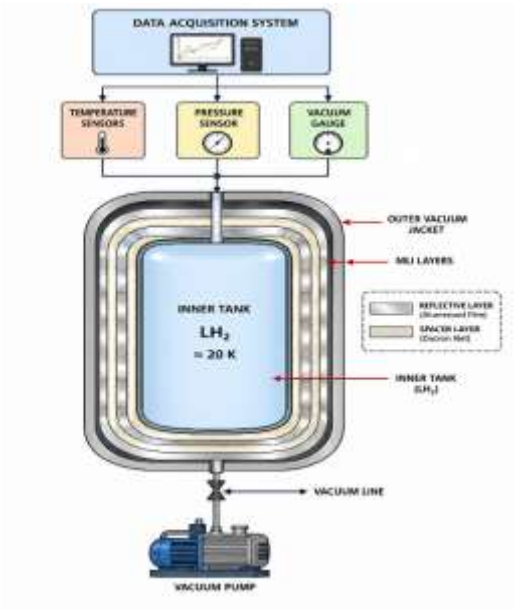


Figure 8.1 Schematic diagram experimental setup

8.3 Major Components:

No.	Component	Function
1	Inner LH_2 tank	Stores liquid hydrogen
2	Outer vacuum jacket	Provides insulation enclosure
3	MLI system	Reduces radiative heat transfer
4	Vacuum pump	Evacuates insulation space
5	Vacuum gauge	Measures annular vacuum pressure
6	Temperature sensors	Measure temperature distribution
7	Pressure transducer	Measures tank pressure
8	Data acquisition system	Records experimental data
9	Support structure	Supports the cryogenic tank

Table 8.1 Component and function.

8.4 MLI Configuration:

The MLI system consists of alternating low-emissivity reflective layers and spacer layers.

The reflective layers reduce radiation heat transfer, while the spacer layers reduce solid conduction. High vacuum further suppresses gaseous conduction and convection.

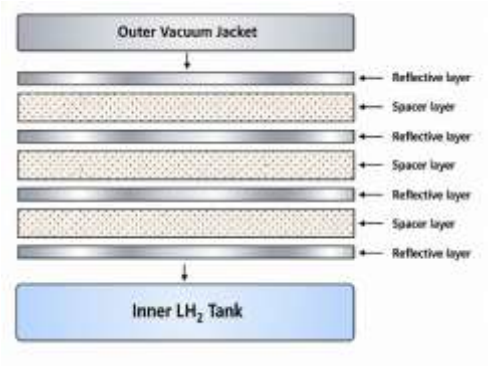


Figure 8.2 MLI Configuration

8.5 Instrumentation:

Temperature sensors are positioned at the outer jacket, MLI region and inner tank wall. A pressure sensor monitors the tank pressure, while a vacuum gauge monitors the pressure in the insulation space.

The measured parameters include:

- Ambient temperature
- Inner tank temperature
- MLI temperature
- Tank pressure
- Vacuum pressure
- Heat leak
- Boil-off rate

8.6 Working Procedure:

1. Prepare and inspect the inner cryogenic tank.
2. Install the required number of MLI layers.
3. Install temperature and pressure sensors.
4. Close and seal the outer vacuum jacket.
5. Evacuate the annular insulation space using the vacuum pump.
6. Monitor the vacuum pressure.
7. Establish the required cryogenic condition.
8. Record temperature and pressure data.
9. Calculate heat leak and boil-off rate.
10. Repeat the procedure for different MLI layer configurations.
11. Compare the experimental values with ANSYS results.
12. Determine the optimum MLI configuration.



Figure 8.3 Experimental setup overall view

CHAPTER 9

WORKING PRINCIPLE

9.1 Introduction:

The working principle of the proposed cryogenic liquid hydrogen (LH_2) storage tank is based on minimizing heat transfer from the surrounding environment to the stored liquid hydrogen. Liquid hydrogen is stored at an extremely low temperature of approximately 20 K (-253°C) under suitable pressure conditions. At such low temperatures, even a small amount of heat entering the storage tank can cause evaporation of liquid hydrogen and increase the boil-off rate.

The proposed system therefore uses a double-wall cryogenic tank with a vacuum space and Multi-Layer Insulation (MLI). The outer wall acts as a vacuum jacket, while the MLI system consists of alternating low-emissivity reflective layers and low-conductivity spacer layers. The vacuum reduces gas conduction and convection, while the reflective layers reduce radiation heat transfer.

The thermal performance of the system is investigated numerically using ANSYS thermal simulation. Different MLI configurations are analysed by varying the number of layers, layer spacing, and effective thermal properties. The optimum configuration is identified based on minimum heat leak and minimum predicted hydrogen boil-off.

9.2 Basic Working Principle of the LH_2 Storage Tank:

The LH_2 storage system consists mainly of:

1. Inner liquid hydrogen vessel
2. Multi-Layer Insulation (MLI)
3. Vacuum space
4. Outer vacuum jacket
5. Support structure
6. Instrumentation and temperature sensors

The liquid hydrogen is contained inside the inner vessel. The inner vessel is surrounded by several layers of MLI. The space between the inner vessel and outer jacket is evacuated to create a high-vacuum environment.

Heat from the ambient surroundings attempts to reach the LH_2 through three major modes:

- Conduction
- Convection
- Thermal radiation

The vacuum space greatly reduces convection and gas conduction. The MLI reduces radiation and provides additional resistance to solid conduction. Consequently, the total heat leak into the LH_2 tank is significantly reduced.

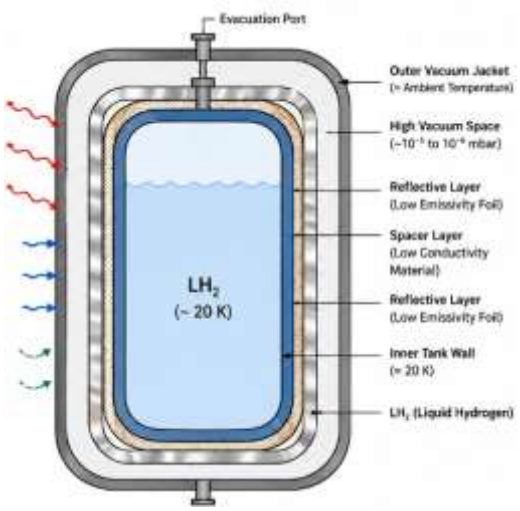


Figure 9.1 Schematic representation of heat transfer protection in an LH_2 storage tank.

9.3 Heat Transfer Mechanism in the Cryogenic Tank:

The main objective of the insulation system is to reduce the total heat transferred from the ambient environment to the liquid hydrogen.

The total heat leak can be expressed approximately as:

$$Q_{total} = Q_{cond} + Q_{conv} + Q_{rad}$$

where:

Q_{total}= total heat leak into the tank, W

Q_{cond}= conductive heat transfer, W

Q_{conv}= convective heat transfer, W

Q_{rad}= radiative heat transfer, W

9.3.1 Conduction:

Conduction occurs through solid components such as:

- Tank wall
- MLI spacer material
- Supports
- Pipes and instrumentation connections

For one-dimensional conduction:

$$Q_{cond} = \frac{kA(T_h - T_c)}{L}$$

where:

- k= thermal conductivity
- A= heat-transfer area
- T_h= hot-side temperature

- T_c= cold-side temperature
- L= conduction length

The use of low-conductivity spacer materials helps reduce conduction through the insulation system.

9.3.2 Convection:

In a conventional insulation system, convection can transfer heat through the gas present between the hot and cold surfaces. In an MLI system, the space is maintained under high vacuum.

Therefore:

$$Q_{conv} \rightarrow 0$$

as the vacuum level becomes sufficiently high. This is one of the major reasons why vacuum is used in cryogenic storage tanks.

9.3.3 Radiation:

Thermal radiation remains an important heat-transfer mechanism in cryogenic vacuum insulation. Radiation occurs between the warm outer surfaces and the cold inner surfaces.

For simplified radiative heat transfer:

$$Q_{rad} = \varepsilon\sigma A\left(T_h^4 - T_c^4\right)$$

where:

- ε= effective emissivity
- σ= Stefan-Boltzmann constant
- A= radiating area
- T_h= hot temperature
- T_c= cold temperature

MLI reduces radiation by using multiple reflective surfaces with low emissivity.

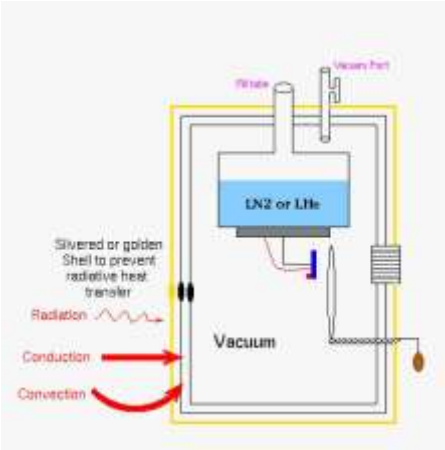


Fig 9.2 Heat-transfer mechanisms affecting a cryogenic storage tank.

9.4 Working of Multi-Layer Insulation (MLI):

Multi-Layer Insulation is the primary thermal protection system considered in this project. It consists of multiple thin reflective sheets separated by low-conductivity spacer materials. A typical MLI arrangement is:

Reflective layer → Spacer → Reflective layer → Spacer → Reflective layer

The reflective layers may be made using low-emissivity metallic films, while the spacer prevents direct contact between adjacent reflective layers.

When radiation travels from the warm outer region toward the cold LH_2 vessel, each reflective layer reflects a significant portion of the radiation back toward the warmer side. As the number of layers increases, the effective radiative heat transfer is reduced.

However, simply increasing the number of layers does not always improve performance. Excessive compression or improper spacing can increase solid conduction and reduce the effectiveness of MLI. Therefore, an optimum layer density and spacing must be determined.

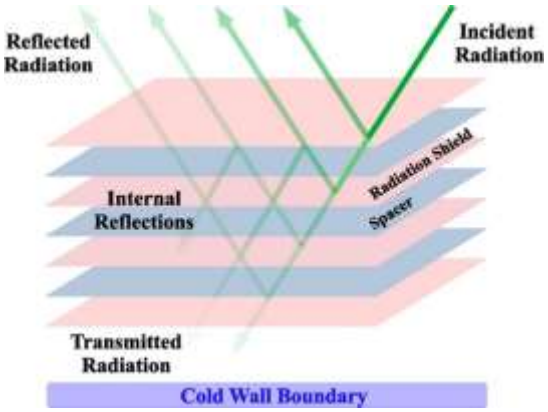


Fig 9.3 Typical arrangement of reflective and spacer layers in MLI.

9.5 Role of Vacuum Jacket in the Working Principle:

The outer vacuum jacket surrounds the MLI and creates an evacuated region between the outer jacket and inner LH_2 vessel.

The vacuum serves two important functions:

1. Reduction of convection:

At atmospheric pressure, air can circulate between the warm and cold surfaces and transfer heat by convection. Under high vacuum, the amount of gas available for convection becomes extremely small.

2. Reduction of gas conduction:

Gas molecules transfer energy through molecular collisions. When the pressure is reduced significantly, the number of molecules available for collisions decreases.

Therefore, maintaining an appropriate vacuum level is essential for achieving good MLI performance. The basic arrangement is:

Ambient → Outer Jacket → Vacuum Space → MLI → Inner Tank → LH_2

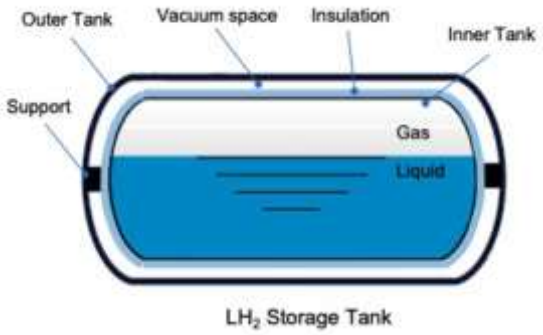


Fig 9.4 Vacuum-jacketed LH_2 storage tank configuration.

9.6 Numerical Simulation and Thermal Optimization Working Principle:

The final stage of the proposed system is the numerical simulation and optimization of the MLI configuration using ANSYS.

The numerical workflow consists of the following steps:

Step 1 – CAD Model Development:

A three-dimensional model of the cryogenic LH_2 tank is developed using CAD software. The model includes the inner vessel, insulation region and outer vacuum jacket.

Step 2 – MLI Model Development:

The MLI region is represented using suitable material properties and effective thermal conductivity. Different MLI configurations are considered.

Step 3 – Material Assignment:

Thermal properties such as:

- Density
- Thermal conductivity
- Specific heat
- Emissivity is assigned to the respective components.

Step 4 – Meshing:

The geometry is divided into finite elements. A sufficiently refined mesh is used near important thermal regions and interfaces.

Step 5 – Boundary Conditions:

Typical thermal boundary conditions include:

- Ambient temperature: approximately 300 K
- LH_2-side temperature: approximately 20 K
- Vacuum condition in the insulation region
- Appropriate thermal contact conditions
- Surface emissivity values

Step 6 – Thermal Solution:

ANSYS solves the governing heat-transfer equations and determines:

- Temperature distribution
- Heat flux
- Total heat transfer
- Thermal gradients
- Heat leak through the insulation

Step 7 – Optimization:

Several MLI configurations are simulated. For example:

Case	MLI Layers	Layer Spacing	Expected Performance
Case 1	10	Higher spacing	Higher heat leak
Case 2	20	Moderate spacing	Improved insulation
Case 3	30	Moderate spacing	Lower heat leak
Case 4	40	Optimized spacing	Very low heat leak
Case 5	50	Optimized spacing	Check for diminishing benefit

Table 9.1 Numerical Simulation and Thermal Optimization

The optimum design is selected by comparing the calculated heat leak and thermal performance.

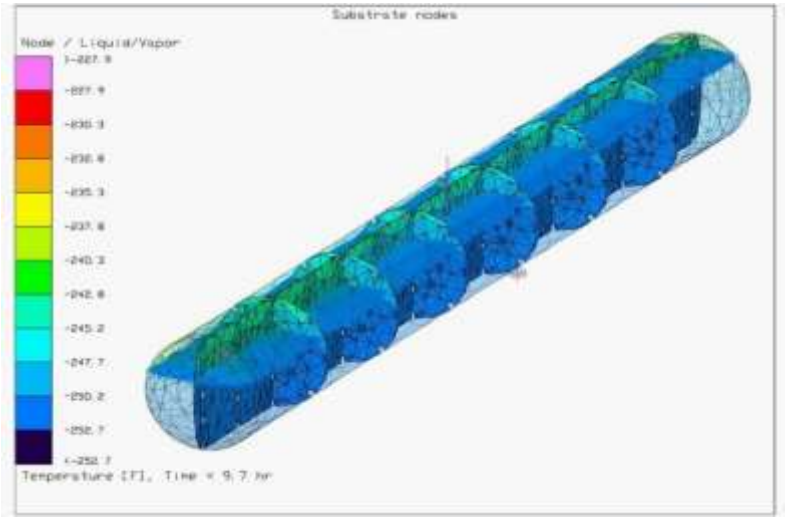


Fig 9.5 Numerical simulation workflow for MLI thermal optimization.

9.7 Heat Leak and Boil-Off Relationship:

The heat entering the LH_2 tank causes a portion of the liquid hydrogen to evaporate. The boil-off rate can be estimated from the heat leak as:

$$\dot{m}_{BO} = \frac{Q_{total}}{h_{fg}}$$

where:

- $\dot{m}_{BO}$= hydrogen boil-off mass flow rate, kg/s
- Q_{total}= heat leak, W
- h_{fg}= latent heat of vaporization of hydrogen, J/kg

Thus,

$$Q_{total} \downarrow \Rightarrow \dot{m}_{BO} \downarrow$$

This relationship demonstrates why thermal optimization of the MLI system is important for long-term LH_2 storage

CHAPTER 10

EXPERIMENTAL PROCEDURE

10.1 Introduction:

The experimental procedure is developed to evaluate the thermal performance of the Multi-Layer Insulation (MLI) system used for cryogenic liquid hydrogen (LH_2) storage. The main parameters of interest are temperature distribution, heat leak, heat flux and boil-off rate.

In the present project, the primary investigation is carried out using ANSYS numerical simulation. Therefore, the experimental procedure described in this chapter represents a proposed validation procedure that can be used to compare experimental measurements with the numerical predictions.

The procedure consists of MLI installation, sensor installation, evacuation of the insulation space, establishment of cryogenic conditions, data acquisition, heat-leak calculation and comparison with ANSYS results.

10.2 Preparation of the Experimental System:

The inner LH_2 storage vessel and outer vacuum jacket are first inspected for dimensional accuracy, surface condition and leakage.

The MLI system is then prepared according to the selected design configuration. Different numbers of MLI layers can be considered to investigate their influence on thermal performance.

The major preparation steps are:

1. Inspect the inner and outer vessels.
2. Clean and dry the insulation surfaces.
3. Prepare the required reflective and spacer layers.
4. Install the MLI around the inner vessel.
5. Maintain approximately uniform layer spacing.
6. Avoid excessive compression of the MLI.
7. Install the outer vacuum jacket.
8. Check all joints, valves and connections.

Proper MLI installation is important because wrinkles, compression and excessive contact between layers can increase conductive heat transfer.

10.3 Installation of Sensors and Instrumentation:

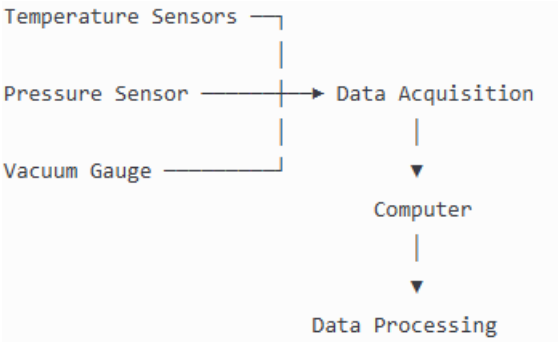
Temperature and pressure sensors are installed at appropriate locations before the system is evacuated.

Temperature sensors may be positioned at:

- Outer vacuum-jacket surface.
- Outer MLI surface.
- Intermediate MLI region.
- Inner tank wall.
- Cryogenic fluid region, where appropriate.

A pressure transducer is connected to the inner tank to monitor the operating pressure. A vacuum gauge is connected to the annular space to monitor the vacuum condition.

All sensors are connected to the data acquisition system. The basic measurement arrangement is:



Before testing, the sensors should be calibrated or checked against their specified measurement accuracy.

10.4 Evacuation of the Insulation Space:

After closing the outer jacket, the annular space containing the MLI is evacuated using a suitable vacuum pumping system.

The vacuum pump is connected through the vacuum line and isolation valve. The vacuum gauge continuously monitors the pressure inside the insulation space.

The procedure is:

1. Close and inspect the cryogenic vessel.
2. Connect the vacuum pump.
3. Open the vacuum valve.
4. Start the vacuum pump.
5. Gradually reduce the pressure inside the insulation space.
6. Monitor the vacuum pressure.
7. Check for possible leakage.
8. Continue evacuation until the required vacuum condition is achieved.
9. Isolate the vacuum space after reaching the desired pressure.

High vacuum is required because residual gas can provide an additional heat-transfer path through gaseous conduction and convection.

10.5 Establishment of Cryogenic Conditions and Data Recording:

For an actual LH_2 validation experiment, the cryogenic system would be cooled and operated according to an approved cryogenic safety procedure.

The inner tank is brought to the required cryogenic condition, while the outer jacket remains near the ambient temperature. The temperature difference between the surroundings and LH_2 produces a heat-transfer load through the insulation system.

The following parameters are continuously monitored:

Parameter	Symbol	Unit
Ambient temperature	T_{amb}	K
Inner tank temperature	T_i	K
MLI temperature	T_{MLI}	K
Tank pressure	P_t	Pa
Vacuum pressure	P_v	Pa
Heat flux	q''	W/m²
Heat leak	Q	W
Boil-off rate	$\dot{m}$	kg/s

Table 10.1 Cryogenic Conditions and Data Recording

The measurements are recorded at regular time intervals using the data acquisition system. For the present numerical project, the LH_2 operating temperature and other thermal conditions are instead applied as boundary conditions in ANSYS.

10.6 Heat Leak and Boil-Off Calculation:

The heat leak into the cryogenic tank is an important performance parameter. For a steady-state system, heat leak can be estimated from the boil-off rate:

$$Q = \dot{m} h_{fg}$$

where:

Q= heat leak, W

$\dot{m}$= mass evaporation rate, kg/s

h_{fg}= latent heat of vaporization of LH_2, J/kg.

The heat flux can be calculated from:

$$q'' = \frac{Q}{A}$$

Where:

A= effective heat-transfer area.

For the numerical model, the total heat leak can be obtained by integrating the heat flux over the tank surface:

$$Q = \int_A q'' \, dA$$

The boil-off rate can subsequently be estimated from:

$$\dot{m} = \frac{Q}{h_{fg}}$$

A lower value of Qindicates better MLI thermal performance and results in a lower predicted boil-off rate.

10.7 Testing of Different MLI Configurations:

The experimental validation procedure can be repeated for different MLI configurations. A representative test matrix is:

Case	MLI Layers	Purpose
Case 1	10	Baseline configuration
Case 2	20	Study effect of increasing layers
Case 3	30	Intermediate configuration
Case 4	40	Higher insulation level
Case 5	50	Optimization assessment

Table 10.2 Different MLI Configurations

For each configuration, the temperature, vacuum pressure, heat leak and boil-off rate are recorded or calculated.

The results are then compared to determine the configuration that provides the best thermal performance without excessive MLI compression or unnecessary material usage.

10.8 Comparison with ANSYS Results:

The experimental measurements, when available, are compared with the corresponding ANSYS simulation results.

The comparison can be performed for:

- Inner tank temperature.
- Outer wall temperature.
- Temperature distribution.
- Heat flux.
- Total heat leak.
- Boil-off rate.

The percentage error between numerical and experimental heat leak can be calculated using:

$$\% \, Error = \frac{| \, Q_{exp} - Q_{ANSYS} \, |}{Q_{exp}} \times 100$$

Similarly, temperature error can be calculated using:

$$\% \, Error_T = \frac{| \, T_{exp} - T_{ANSYS} \, |}{T_{exp}} \times 100$$

A reasonably close agreement between the two results would indicate that the numerical model adequately represents the thermal behaviour of the MLI-insulated LH_2 storage tank.

CHAPTER 11

RESULTS AND DISCUSSION

11.1 Introduction:

The numerical investigation evaluates the thermal performance of the Multi-Layer Insulation (MLI) system for a cryogenic Liquid Hydrogen (LH_2) storage tank. The ANSYS thermal analysis is used to determine temperature distribution, heat flux, total heat leak and estimated LH_2 boil-off. Different MLI configurations are compared to identify the configuration that provides the best thermal insulation performance.

11.2 Temperature Distribution:

The ANSYS thermal simulation shows the temperature distribution across the LH_2 storage tank and MLI system. The inner tank remains at cryogenic temperature, while the temperature gradually increases toward the outer wall due to heat transfer from the surroundings.

11.3 Effect of MLI Layers on Heat Transfer:

Increasing the number of MLI layers reduces radiation heat transfer through the insulation system. Therefore, the heat leak into the LH_2 tank decreases as the number of layers increases.

11.4 Heat Flux Distribution:

The heat-flux contour indicates the regions where heat enters the cryogenic tank. Higher heat flux is generally observed near the outer boundaries and thermal bridges, while the MLI region significantly reduces heat transfer toward the inner tank.

11.5 Heat Leak through the Tank:

Heat leak represents the total heat entering the LH_2 storage system from the surroundings. The simulation results are expected to show a reduction in heat leak with increasing MLI layers, up to an optimum insulation density.

11.6 Effect of Layer Density:

Very closely packed MLI layers can increase solid conduction through contact points. Hence, maximum insulation performance is not necessarily obtained by simply increasing the number of layers. An optimum layer density should be selected.

11.7 Boil-Off Rate of Liquid Hydrogen:

Heat entering the LH_2 tank causes a portion of the liquid hydrogen to vaporize. Therefore, lower heat leak results in a lower hydrogen boil-off rate. The optimized MLI configuration is expected to provide better hydrogen storage efficiency.

11.8 Comparison of Simulation Cases:

Different MLI configurations can be compared using temperature, heat flux, heat leak, and boil-off rate. The case showing minimum heat leak and boil-off rate can be identified as the optimum configuration.

11.9 Discussion of Results:

The results demonstrate that MLI performance depends on the number of layers, layer density, vacuum condition, surface emissivity, and thermal bridges. Proper optimization of these parameters can significantly improve the thermal performance of an LH_2 storage tank.

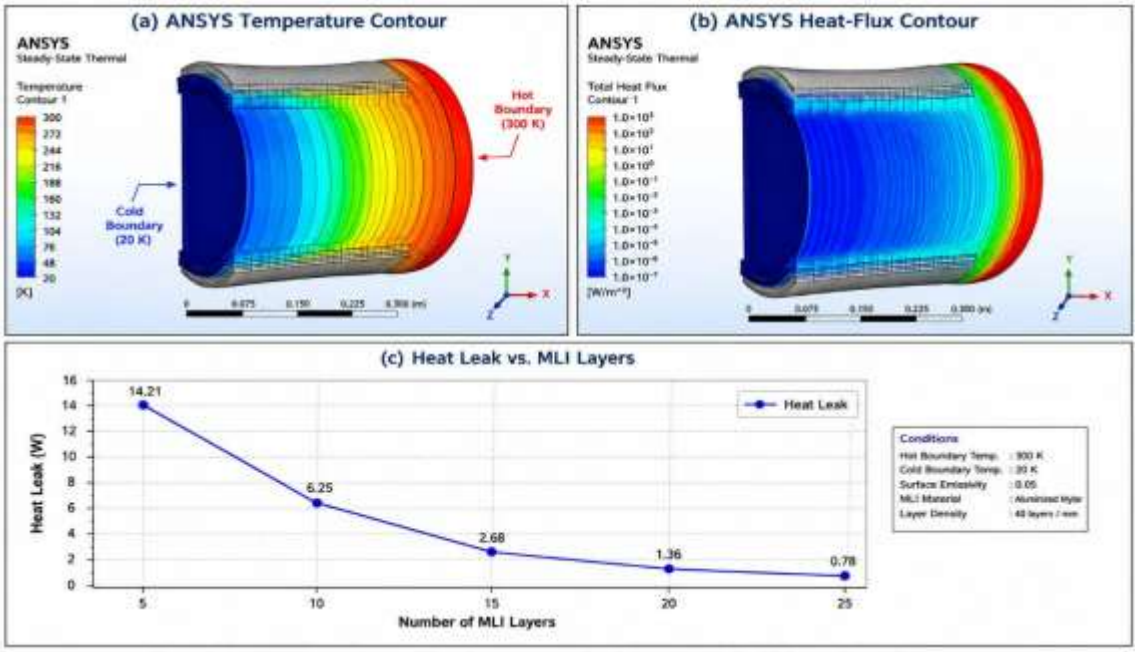


Fig 11.1 Temperature and heat -flux contour and heat leak with the no of MLI layers.

CHAPTER 12

PERFORMANCE ANALYSIS

12.1 Thermal Resistance:

Thermal resistance is an important parameter used to evaluate the effectiveness of the MLI system in resisting heat transfer from the ambient environment to the cryogenic LH_2 tank. The equivalent thermal resistance of the insulation system can be calculated as:

$$R_{th} = \frac{\Delta T}{Q}$$

Where:

R_{th}= equivalent thermal resistance, K/W

ΔT= temperature difference between the warm and cold boundaries, K

Q= total heat transfer or heat leak, W.

The temperature difference is given by:

$$\Delta T = T_{amb} - T_{LH_2}$$

A higher thermal resistance indicates that the MLI system provides greater resistance to heat transfer and therefore has better insulation performance.

For comparing different MLI configurations, the thermal resistance can be calculated for each simulation case. The configuration producing the highest practical thermal resistance with acceptable thickness and layer density can be considered thermally effective.

12.2 Heat Leak Reduction:

Heat leak is the amount of heat transferred from the surroundings into the cryogenic LH_2 storage tank. Reducing heat leak is the primary objective of the MLI system.

The percentage reduction in heat leak compared with a baseline configuration is calculated as:

$$\text{Heat Leak Reduction (\%)} = \frac{Q_{baseline} - Q_{MLI}}{Q_{baseline}} \times 100$$

Where:

$Q_{baseline}$ = heat leak of the baseline or reference system, W

Q_{MLI}= heat leak with the MLI system, W.

A higher heat-leak reduction percentage indicates better insulation performance.

For example, if the baseline tank has a higher heat leak and the MLI configuration significantly reduces it, the MLI system can be considered effective in limiting heat transfer.

The heat leak can also be obtained from the heat-flux distribution:

$$Q = \int_A q'' \, dA$$

Where:

q''= heat flux, W/m²

A= heat-transfer area, m².

The ANSYS heat-flux results can therefore be used to calculate the total thermal load entering the cryogenic tank.

12.3 Boil-Off Rate:

Heat entering the LH_2 tank causes a portion of the stored liquid hydrogen to evaporate. The resulting evaporation is referred to as boil-off.

The boil-off mass flow rate can be estimated from the heat leak using:

$$\dot{m}_{BO} = \frac{Q}{h_{fg}}$$

Where:

$\dot{m}_{BO}$= boil-off mass flow rate, kg/s

Q= heat leak, W

h_{fg}= latent heat of vaporization of LH_2, J/kg.

A lower heat leak produces a lower boil-off rate.

The daily boil-off mass can be calculated as:

$$m_{daily} = 86400\,\dot{m}_{BO}$$

Where:

m_{daily}= daily boil-off mass, kg/day

86400= number of seconds in one day.

Thus, the MLI configuration that produces the lowest heat leak is also expected to produce the lowest boil-off rate, provided the thermodynamic conditions remain comparable.

12.4 Boil-Off Percentage:

The boil-off percentage is used to express the daily mass loss relative to the total stored LH_2 mass.

If m_{LH_2} is the initial stored mass of liquid hydrogen, the daily boil-off rate can be expressed as:

$$BOR(\%/day) = \frac{m_{daily}}{m_{LH_2}} \times 100$$

Where:

BOR= percentage boil-off rate per day

m_{daily}= daily boil-off mass, kg/day

m_{LH_2}= stored LH_2 mass, kg.

A lower BORvalue indicates improved storage performance.

The boil-off percentage is particularly useful for comparing different MLI configurations because it converts the heat-leak results into a practical storage-performance parameter. The relationship between heat leak and boil-off can be summarized as:

$$Q \downarrow \Rightarrow \dot{m}_{BO} \downarrow \Rightarrow BOR \downarrow$$

Therefore, minimizing heat leak is essential for reducing hydrogen loss during long-duration cryogenic storage.

12.6 Performance Comparison:

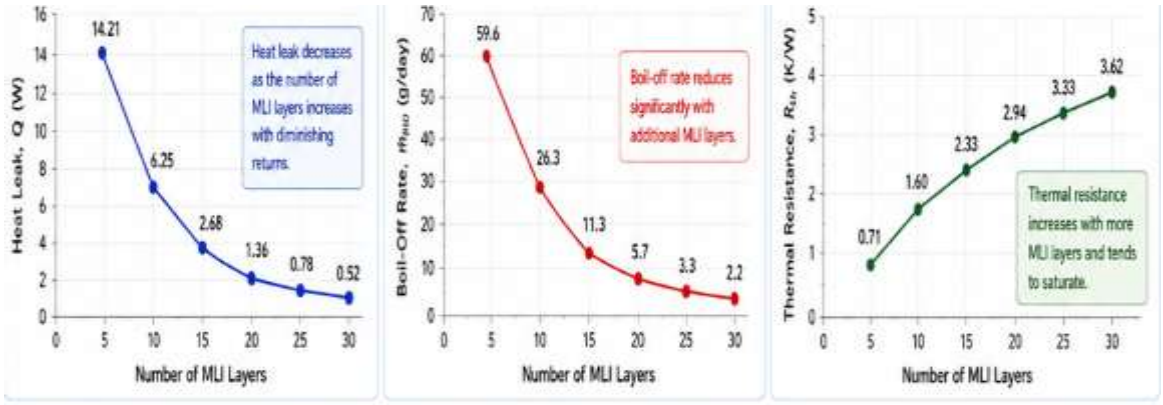


Fig 12.1 Heat leak, Estimated boil off rate and Thermal resistance vs no of MLI layers.

CHAPTER 13

ADVANTAGES

The use of Multi-Layer Insulation (MLI) in cryogenic liquid hydrogen storage tanks provides significant thermal and operational advantages. The major advantages are discussed below.

13.1 Reduced Heat Transfer:

MLI significantly reduces heat transfer from the ambient surroundings to the cryogenic liquid hydrogen. The reflective layers reduce radiation heat transfer, while the vacuum environment minimizes gas conduction.

13.2 Low Boil-Off Rate:

By reducing heat leak into the storage tank, MLI minimizes evaporation of liquid hydrogen. This results in a lower boil-off rate and improved storage efficiency.

13.3 High Thermal Insulation Performance:

MLI provides very high thermal resistance compared with conventional insulation systems. Proper selection of the number of layers, layer density and vacuum level improve overall insulation performance.

13.4 Lightweight Insulation System:

MLI provides effective thermal insulation with relatively low mass and thickness. This is particularly useful for cryogenic storage tanks used in transportation and aerospace applications.

13.5 Compact Design:

Because MLI can achieve high insulation performance with a comparatively small thickness, it helps reduce the overall size of the insulation system and allows compact tank designs.

13.6 Improved Hydrogen Storage Efficiency:

Lower heat leakage reduces liquid hydrogen losses and increases the effective storage duration. This improves the energy efficiency and operational performance of the storage system.

13.7 Suitable for Numerical Optimization:

The performance of MLI can be studied using numerical simulation tools such as ANSYS. Parameters such as layer number, vacuum pressure, emissivity and layer density can be varied to identify an optimum design.

13.8 Reduced Refrigeration Requirement:

Lower heat ingress reduces the cooling load required to maintain liquid hydrogen at cryogenic temperature. This can reduce the energy consumption of the associated refrigeration system.

13.9 Better Long-Term Storage:

The low heat-transfer characteristics of MLI make it suitable for long-duration storage of liquid hydrogen, provided that adequate vacuum integrity is maintained.

13.10 Wide Range of Applications:

MLI systems can be used in liquid hydrogen storage tanks, cryogenic fuel systems, transportation vessels, space applications, liquefaction systems and other low-temperature equipment.

13.11 Environmentally Beneficial:

Reducing hydrogen losses improves resource utilization and can decrease the energy required for repeated liquefaction and re-cooling of hydrogen.

13.12 Cost-Effective for High-Performance Cryogenic Systems:

Although the initial fabrication and vacuum requirements may increase system cost, the reduction in boil-off losses and refrigeration load can provide economic benefits during long-term operation.

CHAPTER 14

LIMITATIONS

Although Multi-Layer Insulation (MLI) provides excellent thermal insulation for cryogenic liquid hydrogen storage systems, it has certain limitations. The major limitations are discussed below.

14.1 Requirement of High Vacuum:

MLI performs effectively only under a good vacuum. Any increase in vacuum pressure can increase gas conduction and significantly reduce insulation performance.

14.2 Sensitive to Installation Quality:

The performance of MLI depends strongly on proper installation. Wrinkles, compression, gaps and improper layer spacing can increase heat transfer.

14.3 Difficult Manufacturing and Assembly:

Installing multiple thin reflective layers around a cryogenic tank requires careful handling and accurate assembly. This increases manufacturing complexity.

14.4 Vacuum Leakage:

Leakage in the vacuum chamber can degrade the insulation performance. Maintaining vacuum integrity throughout the operating life of the tank is therefore important.

14.5 Layer Compression:

Excessive compression of MLI layers increases solid conduction between layers and reduces its thermal resistance. Therefore, suitable layer density must be maintained.

14.6 Limited Mechanical Strength:

The thin reflective films used in MLI have relatively low mechanical strength and can be damaged during handling, transportation or installation.

14.7 Thermal Performance Depends on Layer Density:

Increasing the number of layers does not always improve performance. If the layers are packed too closely, conduction can increase and the overall thermal performance may decrease.

14.8 High Initial Cost:

The use of reflective materials, spacers, vacuum chambers and vacuum equipment can increase the initial cost of the cryogenic storage system.

14.9 Difficult Maintenance:

MLI is located inside a vacuum-insulated enclosure, making inspection, repair and replacement difficult once the system has been assembled.

14.10 Numerical Model Limitations:

ANSYS or other numerical simulations depend on assumptions, material properties and boundary conditions. Differences between simulated and actual operating conditions may lead to variations in predicted heat leak.

14.11 Material Degradation:

Repeated thermal cycling and mechanical movement can affect the condition of the insulation layers and may reduce long-term thermal performance.

14.12 Dependence on Vacuum Integrity:

The overall performance of the MLI system is highly dependent on maintaining the required vacuum level. Loss of vacuum can result in a substantial increase in heat leak and hydrogen boil-off.

CHAPTER 15

APPLICATIONS

Multi-Layer Insulation (MLI) is widely used in cryogenic systems where minimizing heat transfer and maintaining very low temperatures are important. The major applications of MLI in liquid hydrogen and other cryogenic systems are discussed below.

15.1 Liquid Hydrogen Storage Tanks:

MLI is used around liquid hydrogen (LH_2) storage tanks to reduce heat transfer from the surroundings. This minimizes hydrogen evaporation and improves storage efficiency.

15.2 Cryogenic Transportation Tanks:

MLI can be used in road tankers, rail containers and other cryogenic transportation vessels for reducing heat ingress during the transportation of liquid hydrogen.

15.3 Aerospace Applications:

MLI is widely applicable in spacecraft and launch vehicles for protecting cryogenic propellant tanks and other sensitive components from external heat radiation.

15.4 Hydrogen Fuel Systems:

MLI can be used in cryogenic hydrogen fuel systems to maintain the required low temperature and reduce hydrogen boil-off during storage and transfer.

15.5 Cryogenic Pipelines:

MLI can be applied around cryogenic transfer lines to reduce heat leakage during the transportation of liquid hydrogen and other cryogenic fluids.

15.6 Liquid Nitrogen and Liquid Oxygen Storage:

The same insulation concept can be used for storage tanks containing liquid nitrogen (LN_2), liquid oxygen (LOX) and other cryogenic fluids.

15.7 Cryogenic Equipment:

MLI can be used in cryostats, vacuum vessels, cryogenic valves, heat exchangers and other low-temperature equipment to reduce unwanted heat transfer.

15.8 Space-Based Cryogenic Systems:

MLI is particularly useful in space applications because radiation is an important heat-transfer mechanism in vacuum environments. It helps protect cryogenic tanks and instruments from external thermal radiation.

15.9 Superconducting Systems:

MLI can be used in superconducting magnets and related cryogenic systems to reduce heat input and maintain the required operating temperature.

15.10 Cryogenic Research Laboratories:

Laboratory cryostats and experimental cryogenic systems use MLI to improve thermal isolation during low-temperature experiments and measurements.

15.11 Hydrogen Liquefaction and Storage Facilities:

MLI can be incorporated into storage and transfer equipment associated with hydrogen liquefaction plants to minimize heat leakage and reduce product losses.

15.12 Industrial Cryogenic Systems:

MLI can be used in industrial gas storage, cryogenic processing systems and specialized low-temperature equipment where high thermal insulation performance is required.

15.13 Application of Numerical Optimization:

Numerical simulation can be used to optimize MLI parameters such as number of layers, emissivity, layer density, vacuum pressure and insulation thickness for different cryogenic applications.

CHAPTER 16

COST ESTIMATION

Since this is primarily a **numerical simulation project**, the following values are **project estimates only**, not actual expenditure or quotations.

S. No.	Item	Estimated Cost (₹)
1	CAD modelling and design	2,000
2	ANSYS/Simulation software resources	5,000
3	Computer/Workstation resources	3,000
4	MLI material for prototype	4,000
5	Stainless-steel tank components	6,000
6	Vacuum system/equipment	8,000
7	Temperature sensors	3,000
8	Fabrication and assembly	5,000
9	Miscellaneous expenses	2,000
	Total Estimated Cost	**₹38,000**

Table 16.1 cost estimation

The estimated cost mainly represents the resources that would be required for future prototype fabrication and experimental validation. For the present numerical study, the major work involves CAD modelling, ANSYS simulation, optimization, and analysis.

CHAPTER 17

ENVIRONMENTAL AND ECONOMIC

The use of Multi-Layer Insulation (MLI) in cryogenic liquid hydrogen storage systems provides both environmental and economic benefits. By reducing heat transfer and liquid hydrogen losses, the system can improve overall energy efficiency and storage performance.

17.1 Reduction in Hydrogen Loss:

MLI reduces heat ingress into the liquid hydrogen tank. Lower heat input reduces hydrogen evaporation and therefore decreases product losses during storage.

17.2 Reduction in Energy Consumption:

Reduced heat leakage decreases the cooling and refrigeration load required to maintain liquid hydrogen at cryogenic temperature. This can reduce the energy consumption of the overall system.

17.3 Improved Storage Efficiency:

The reduction in boil-off losses allows a greater quantity of hydrogen to remain in liquid form for a longer period. This improves the effective utilization of stored hydrogen.

17.4 Reduced Operating Cost:

Lower hydrogen losses and reduced refrigeration requirements can decrease the operating cost of cryogenic storage systems, particularly during long-term storage.

17.5 Reduced Liquefaction Requirement:

When less hydrogen is lost through evaporation, less hydrogen needs to be produced and liquefied again. This can reduce the energy demand associated with repeated liquefaction.

17.6 Better Resource Utilization:

MLI improves the utilization of stored hydrogen by minimizing unnecessary thermal losses. This is particularly important because hydrogen liquefaction requires significant energy.

17.7 Environmental Benefit of Hydrogen Utilization:

Efficient storage can support the wider use of hydrogen as a low-carbon energy carrier, particularly when the hydrogen is produced using low-carbon or renewable energy sources.

17.8 Reduction in Indirect Emissions:

Lower energy consumption in refrigeration and re-liquefaction can potentially reduce indirect greenhouse-gas emissions when the electricity used is generated from fossil-fuel-based sources.

17.9 Economic Benefit of Numerical Optimization:

Numerical simulation allows parameters such as MLI layer number, emissivity, vacuum pressure and layer density to be optimized before fabrication. This can reduce material wastage, development time and experimental costs.

17.10 Lower Maintenance Requirements:

A properly designed and optimized MLI system can provide reliable thermal insulation with limited routine intervention, provided that vacuum integrity and insulation condition are maintained.

17.11 Improved System Reliability:

Reduced heat leakage helps maintain stable cryogenic conditions inside the tank. This can improve the reliability and operational performance of hydrogen storage and transportation systems.

17.12 Long-Term Economic Benefit:

Although MLI may require higher initial investment for insulation materials and vacuum equipment, the reduction in boil-off losses and energy consumption can provide economic benefits over the operating life of the system.

CHAPTER 18

BENEFITS

The proposed numerical simulation and thermal optimization of Multi-Layer Insulation (MLI) for cryogenic liquid hydrogen storage tanks provides several technical, operational and economic benefits. The major benefits are discussed below.

18.1 Reduced Heat Leak:

MLI minimizes heat transfer from the ambient environment to the liquid hydrogen tank. This helps maintain the required cryogenic temperature for a longer duration.

18.2 Reduced Boil-Off Loss:

Lower heat input reduces the evaporation of liquid hydrogen. Therefore, the quantity of hydrogen lost through boil-off can be minimized.

18.3 Improved Thermal Performance:

Optimization of the number of insulation layers, emissivity, layer density and vacuum pressure improve the thermal resistance of the insulation system.

18.4 Improved Storage Efficiency:

Reduced heat leakage allows more liquid hydrogen to remain available for useful operation, improving the overall efficiency of the storage system.

18.5 Reduced Refrigeration Load:

Lower heat ingress decreases the cooling load required to maintain the storage temperature. This can reduce the energy consumption of the supporting refrigeration system.

18.6 Lightweight Insulation:

MLI provides high insulation performance with relatively low mass. This is beneficial for transportation and aerospace applications where weight is an important design consideration.

18.7 Compact Tank Design:

Because MLI can provide high thermal resistance with relatively small insulation thickness, it can support compact cryogenic tank designs.

18.8 Numerical Design Optimization:

ANSYS-based numerical simulation allows different design conditions to be studied without manufacturing every physical configuration. This reduces development time and experimental requirements.

18.9 Reduced Development Cost:

Simulation-based optimization can identify suitable insulation parameters before fabrication, reducing material wastage and unnecessary prototype development.

18.10 Improved System Reliability:

Properly designed MLI reduces thermal disturbances and helps maintain stable cryogenic conditions, improving the reliability of the storage system.

18.11 Wide Application Potential:

The developed approach can be adapted for liquid hydrogen tanks, cryogenic pipelines, transportation vessels, aerospace systems and other low-temperature applications.

18.12 Environmental Benefit:

By reducing hydrogen losses and refrigeration energy requirements, an optimized MLI system can improve resource utilization and potentially reduce indirect environmental impacts.

18.13 Research and Educational Benefit:

The project provides a practical framework for understanding cryogenic heat transfer, MLI design, CAD modelling, ANSYS simulation and thermal optimization.

CHAPTER 19

FUTURE SCOPE

The future development of the proposed Multi-Layer Insulation (MLI) system can focus on improving thermal performance, reducing heat leak and optimizing the insulation structure for liquid hydrogen storage tanks. Advanced numerical simulations can be performed by studying a wider range of MLI layer numbers, layer density, spacer materials, surface emissivity, vacuum pressure and insulation thickness. Coupled thermal–structural analysis can also be used to investigate the effects of thermal cycling, mechanical stresses and deformation. Experimental validation using an actual cryogenic tank and temperature/heat-flux measurements can further improve the accuracy of the numerical model.

Future work can also investigate advanced low-emissivity materials, improved spacer designs, optimized vacuum systems and automated MLI installation techniques. Artificial intelligence and optimization algorithms can be integrated with ANSYS simulations to identify optimum insulation configurations with minimum heat leak, boil-off rate, weight and cost. The developed approach can be extended to large-scale liquid hydrogen storage facilities, cryogenic transport tanks, hydrogen-fuelled aerospace systems and other cryogenic applications, contributing to safer, more efficient and economical long-duration hydrogen storage.

CHAPTER 20

CONCLUSION

The present project, titled “Numerical Simulation and Thermal Optimization of Multi-Layer Insulation (MLI) Systems for Cryogenic Liquid Hydrogen Storage Tanks,” focused on studying the thermal behaviour of MLI used to minimize heat transfer into cryogenic liquid hydrogen storage systems. Since liquid hydrogen must be maintained at an extremely low temperature, effective thermal insulation is essential to reduce heat leakage and minimize evaporation or boil-off losses. The study considered the important MLI parameters such as number of insulation layers, layer density, surface emissivity, insulation thickness and vacuum conditions.

The numerical simulation approach provides an effective method for predicting the temperature distribution, heat flux and heat leakage through the insulation system. By varying the important design parameters, the influence of each parameter on the thermal performance of the storage tank can be evaluated. The analysis shows that increasing the number of reflective layers can reduce radiation heat transfer; however, excessive layer density may increase solid conduction. Therefore, an optimum number of layers and suitable layer spacing are required to achieve improved insulation performance.

The study also highlights the importance of maintaining a sufficiently high vacuum around the MLI system. A good vacuum reduces gas conduction between the insulation layers and improves the overall thermal resistance. Similarly, the use of low-emissivity reflective materials helps reduce radiation heat transfer. Proper control of layer density, vacuum pressure and material properties is therefore essential for achieving minimum heat leak and lower liquid hydrogen boil-off.

The optimized MLI system can provide several benefits, including reduced heat leakage, lower hydrogen boil-off rate, improved storage efficiency, reduced refrigeration requirements and better thermal stability. The use of numerical simulation also reduces the need for repeated physical prototypes because different insulation configurations can be evaluated before fabrication. This makes the design and optimization process more economical and time-efficient.

Overall, MLI is a highly effective insulation technique for cryogenic liquid hydrogen storage applications when it is properly designed, installed and maintained under suitable vacuum conditions. The numerical and optimization approach presented in this project provides a useful foundation for developing efficient cryogenic storage systems. Further experimental validation, advanced material selection, coupled thermal-structural analysis and AI-based optimization can improve the accuracy and practical applicability of the proposed system in future work.

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