THE OPTIMIZATION OF LAYER DENSITIES FOR MULTILAYERED INSULATION SYSTEMS BY USING ANSYS

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ABSTRACT

Now-a days cryogenic insulation performance and reliability, durability are continually improving, they are more frequently used by physicists in their laboratory experiments for commercial and space applications. Cryogenic propellant storage is a crucial part of future space exploration. Efficient thermal insulation is one of the technologies for the long-duration missions. The work deals with the thermal performance of variable density multilayer insulation with different configurations and spacers. For conventional multilayer insulation blankets, it is difficult to control the layer density and the thermal insulation performance degrades due to the increase in conductive heat leak through interlayer contacts. The configuration of VDMLI was proposed by predicting the internal temperature profiles and maximizing the thermal resistance based on the basic layer model. A mathematical model will be developed to assess the temperature profile and effective heat transfer coefficient of the VDMLI. It is expected that the insulation performance of MLI could be improved considerably after replacing the regular uniform configuration with the optimized variable density configuration. Further, it is also proposed to study the effect of different spacing materials viz., none-woven cloth, Dacron net, polyether ketone (PEEK) etc.

KEYWORDS: VDMLI with different Densities & Internal Heat Transfer between Layers

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Nomenclature

- Cold body temperature, T₁
- Hot body temperature, T₆
- Thermal conductivities, K
- Interface temperatures
- Heat transfer coefficient, Q

INTRODUCTION

Definition

Cryogenics is derived from the Greek language “cryo” which means ice. Cryogenics can define as the branch of physics and engineering which deals with the production of “freezing” and fuel purpose for space vehicles and the study of materials at such low temperatures. If it can be liquefied or ends cryogenics temperature

below -150°C (123K) or -240°F (220 o R) come under the definition of cryogenics. Below this temperature, all the permanent gases like argon, neon, nitrogen, oxygen, hydrogen, and helium start condensing.

How Cryogenics Starts

The reduction of heat in the operation of air conditions that keeps homes and companies cool. Refrigerators and freezers are used to preserve the food for the long period.

Generally, three forms of heat transfer are radiation, conduction, and convection. Insulation a key for long duration mission required cryogenic storage. Multilayer insulations for cryogenic storage are designed for high vacuum conditions they consist of radiation shield with a spacer with a low conductivity material in between shields. MLI have different physical properties by nature, making it difficult to apply to compare geometries. MLI very sensitive to mechanical compression and edge effects required careful attention to details during all phases of its installations. Cryogenics applications are fertilizers, cryogrinding, medical, cryopreservation of food, high-speed transport, space applications.

Application of Cryogenics

Basics of Cryogenics

Temperature, pressure and magnetic field are three important parameters for studies, which can alter the behavior of a material quite drastically. The physics at low temperature is extremely interesting and its physics of order. Lower the temperature, more subtle is the nature of this order. Superfluidity in the two liquids (liquid ^3He and liquid ^4He).

Space

Cryogenics has two types of applications in the space, named as a fuel (liquid nitrogen, liquid oxygen) and to cool the detectors below their operational temperature. Hydrogen and oxygen are considered the best rocket propellants for space application because of their produce high specific impulse. Hydrogen is used as a fuel and oxygen as an oxidizer both combine to form cryo fuel and produces trust. Both the gases being light needs large volumes and therefore used in the form of liquids to conserve space.

Fertilizers

Compounds of nitrogen such as ammonium nitrate (NH_4NO_3) and ammonium sulphate ($(\text{NH}_4)_2\text{SO}_4$) are important for plant growth for making proteins. Plants cannot take nitrogen from atmospheres but it can absorb from the soil water. Synthetic fertilizers are produced by a combination of nitrogen and hydrogen into ammonia.

Cryogrinding

Cryogrinding technique is widely used for all types of plastic, rubber, pharmaceuticals, cosmetics, and spices. The material becomes very delicate at cryogenic temperatures.

Medical

The utility of cryogenics in the medical sector is vast and it helps the public. Magnetic resonance imaging (MRI), based upon the principle of Nuclear Magnetic Resonance (NMR) has become an extremely important and useful diagnostic tool with all the hospitals across the world. MRI needs a fixed magnetic field. Such a stable field can only be provided by a superconducting magnet. MRI uses a huge size superconducting magnet cooled by liquid helium. The magnet runs

continuously forever and without a power supply. Another main application is the cryopreservation of human blood, sperms, semen, human ovary, human embryos, bone marrow, lungs, kidneys, liver, and platelets.

Cryopreservation of Food

More varieties of food items like vegetables, marine products, fruits, flesh (meat) are biodegradable in nature. They deteriorate fast because of bacteria, fungi, and other chemical reaction slow down below -1200C the life of products can be significantly increased by instant quick freezing (IQF) technique. The technique seals to preserve the taste, aroma, texture or the nutrition value of the food product.

High Speed Transport

Superconducting magnets operate on the track and aluminum strips run along the magnet in a concrete slab. At a high speed, eddy currents produced in the Al strips by the moving magnets in high enough to produce an opposing field which lifts the train above the track. The friction between the wheels and the train picks up the high speed.

LITERATURE REVIEW

To design any VDMLI, there is some basic design configuration. The combination of foam and multilayer insulation model is considered as five segments. The first segment is foam insulation and the remaining 2 to 5 segments contains different layer densities. Here two approaches are considered, one is variable density multilayer insulation is model by layer to layer while in the second approach, a semi-empirical model is applied. A.Hedayat et al (2002). Theoretical and experimental investigation of the thermal performance of VDMLI with a different configuration of spacers. Optimizing the internal temperature profile and maximizing the thermal resistance-based layer by layer model. B.wang et al (2002). Basic fundamental laws are explained, conduction, convection, radiation and thermal resistance, an emissivity of the materials which were used for cooling at low temperatures. B.Baudouy et al (2015). Material properties and their thermal conductivities, thermal expansions, specific heat and here temperature range divided into 4 type from 4K to 300k. E.D.Marquardt et al (2000). Flexible multilayer insulation material which can be used in high and low temperatures environment has been analyzed. A mathematical model has been developed to describe the heat flux through flexible multilayer insulation, heat transfer consists of thermal radiation, solid spacer and gas heat transfer. Jinjing Chen et al (2010). The combination of radiation and conduction heat transfer in multilayer perforated insulation used in space. According to the model, calculation of temperature field in MLPIM and the model of inner radiation. The difference equations have been solved by the iterative method combining with ADI method (alternating direction implicit method). The effect of the main parameter such as layer density, screen emissivity and perforation coefficient on the thermal performance has been analyzed. Peng Li et al (2006). How cryogenic is started and how it implements. The brief outline of cryogenics, covering the whole period from 1877 up to present day. R.G.Scurlock et al (1989). Multilayer insulation is an alternative layer of shield and spacer in high vacuum. Due to unpredictable changes in parameters such as winding pressure, uniform contacting and interstitial pressure, accurate theoretical prediction of MLI performance is very difficult.). R.G.Scurlock et al (1990). The calculation of densities by a complex physics-based algorithm developed by McIntosh. All formulas generated no of layers and layers densities as geometric variable solving for heat flux. By converting the equation from heat flux to thermal conductivity by using Fourier law, then the equation becomes a function of layer densities, temperature, and material properties. W.L.Johnson et al (2010).

History of MLI

Cryogenics is the branch of physics which deals with low temperatures. It also defined as the production of low temperatures below 123K. Cryogenics is used highly in space systems, air conditions and refrigeration systems to keep cooling due to high radiation and heat leakages in the system. In space systems, cryogenic insulation is used to reduce the external heats and leakages. Cryogenic insulation is a barrier for liquid propellants to keep cool.

MLI was first designed by Peterson in 1958 and after many decades MLI was improved in many formats, style, and configuration. Cryogenic insulation is best for reducing the overall heat transfer and MLI works under vacuum conditions with pressure below 10^{-3} torr. MLI material is Aluminum, titanium, gold, silver, copper etc. Aluminum is very cheapest material among them. Mainly aluminum is used due to its thermal conductivity is low than other materials. Production of aluminum is very high because it's minimum at cost.

Theory of Insulation

Selecting the insulation for a certain application is a compromise like an economy, convenience, weight, ruggedness, volume, and insulation effectiveness. The techniques of high-quality insulation, some insulations give less perfect insulation methods that may be desirable for special applications. The effectiveness of a thermal insulation is considered on the basis of thermal conductivity. Mainly the insulation parameters are the type of insulation, thermal conductivity, emissivity, and boundary temperatures, densities.

Thermal conductivity is defined as the property of all same kind of (homogeneous) body measured by the ratio of steady-state heat flux (time rate of heat flow per unit area) and temperature gradient (temperature difference per unit length of heat flow path) in the direction perpendicular to the area. In steady state can find the interface temperatures and overall heat transfer. Thermal conductivity must be specified with respect to the mean temperature. Because of the complex interactions of several heat transfer mechanisms, the term "apparent thermal conductivity". The thermal insulation depends on the temperature and the boundary surfaces, its density, the type and pressure of the gas contained within it. Emissivity is the ratio of emission of radiant energy by an opaque material to the emission of a perfect emitter (a blackbody) at the same temperature.

All three heat transfer modes considered when designing an insulation system. Conduction and convection are normally the only modes considered when dealing with normal room temperature systems. However, heat transfer can be greatly reduced when reducing the number of factors to eliminate. One method is to remove all interstitial gas in the system. Convection heat transfers reduce to zero once all fluid is removed. Conduction heat transfer can be reduced by eliminating contact between surfaces however this is hard to do outside if there is a load between two surfaces. Thermal radiation can be greatly reduced by placing reflective shields between radiating bodies.

Multilayer Insulation

One common radiation fence (barrier) used in the cryogenic application is known as multilayer insulation (MLI). The space program development develops the MLI starts around the 1960's. The MLI generally contains multiple layers of reflective shields separated by spacers having low conductivity and vacuum is an additional parameter in MLI.

MLI consists of many radiation shields arranged in parallel as close as possible without touching each another. Each layer is added by spacer material such as polyester, nylon or Mylar, fiberglass, rayon net etc. The aluminum foil is

carefully wrapped around the container it covers the entire surface of the inner vessel. Spacer material, placed between the layers to completely prevent the separate coverings of foil from contacting should they touch, a thermal short circuit will occur and increase the heat transfer. As the number of layers increases the insulation capacity is also increased. MLI is designed to work under high order vacuum, i.e., pressure below about 7.5×10^{-5} torr (10 mPa). Each layer contains a thin, low emissivity radiation shield, enabling the layer to reflect a large percentage of the radiation it receives from a warm surface. The radiation shields are separated from each other to reduce the heat transferred from shield to shield by solid conduction. The gas in the space between shields is removed to decrease the conduction by gas molecules. Each component of the insulation is designed specifically to perform a particular function.

Radiation Shields: to decrease radiation.

Spacers: decrease solid conduction.

Evacuation: to decrease gas conduction.

Spacers classified into 4 types:

- Multiple resistance spacers.
- Point contact spacer.
- Single component multilayer insulation.
- Composite spacers.

Multiple Resistance Spacers

Two surfaces are in contact, no force against each other, present a relatively high resistance to heat flow at the points of contact. Material such as a fibrous mat arranged with fibers in parallel. The heat should flow through fiber to fiber to reach next shield, the greater the resistance per unit thickness the mat presents to the heat flow. Fibers are not plane perpendicular to the heat flow will act as thermal short across the mat.

Point Contact Spacers

Separating the neighboring radiation shields is to place particles along the surface of the shields. If the typical dimension of the single particle is small compared to the distance between two particles along the shield, the contacts between the shields can be called as point contacts.

Examples of point contact spacers: (a) spheres between shields, (b) point contacts between shields, and (c) screens between shields.

Figure 1: Types of point contact

Single Component Multilayer Insulation

Radiation shields can be spaced from each other without adding any spacer material. Crinkling the shields produce random small area contacts that create contact resistances high enough to reduce conductive heat transfer.

Composite Spacers

The combination of two or more materials with a selected material to perform a specific function. A spacer may consist of a very light, dimensionally stable, thin material of tensile properties that will be an easy application of insulation. The thermal properties of this material are not of primary importance. The second material is not specific tensile strength, only acceptable thermal properties.

Spacers Material

Below listed materials can be used as the spacer for multilayer insulation. Depending on the required performance, one or more layers of the spacer material may be applied between neighbor radiation shields. To reduce the weight of the spacer, the material may be perforated, as long as with conduction heat transfer limitations.

Table 1: Low-Conductivity Spacer Materials are Glass Fiber Mat, Nylon Net, and Glass Fabric, has used to Separate Aluminum Foil Shields, showed in below table

Comparison of Typical Spacer Materials					
Spacer Material	Thickness (in.)	Weight Per Area		Dimensional Stability	Tensile Strength
		lb/ft ² (×103)	g/m ²		
Foam	0.020	3.3	16	Good	Poor
Glass paper	0.08	10.9	53	Fair	Poor
	0.04	6.1	30	Fair	Poor
Crinkled polyester film	0.00025	1.5	7.3	Poor	Excellent
Glass fabric	0.0015	3.8	19	Very Poor	Poor
Silk screen	0.003	1.2	5.9	Good	Good
Nylon screen	0.007	2.7	13	Good	Good
Vinyl-coated fiber glass screen	0.020	15.4	75	Excellent	Excellent

Table 2: Thermal Conductivity of Multilayer Insulation

Apparent Mean Thermal Conductivity of Some Selected Multilayer Insulations of Aluminum Foil Spaced with Various Materials					
Sample Thickness (cm)	Number of Shields (per cm)	Density (g/cm ³)	Cold wall Temperature ² (K)	Thermal Conductivity [μ W/(cm K)]	Spacer Material
3.7	26	0.12	76 20	0.7 0.5	Glass fiber mat
2.5	24	0.09	76	2.3	Nylon net
1.5	76	0.76	76	5.2	Glass fabric
4.5	6	0.03	76	3.9	Glass fiber (unbonded)
2.2	6	0.03	76	3.0	Glass fiber (unbonded)

Radiation Shields

The major requirement for a radiation shield is low emissivity. Materials like Silver, aluminum, gold is low emissivity that can be used as coatings for shields or to form thin foils. The emissivity of aluminum is only slightly higher

than that of clean silver, but whereas silver exposure in air, aluminum forms a very thin layer of aluminum oxide that prevents further degradation of the surface. Aluminum is low cost and easily available in different thickness of foil and as a coating on a variety of metallic and non-metallic surfaces. The emissivity of materials is shown in below diagram.

Figure 2: Emissivities of the Materials

Foam Insulation

Foam insulation is a cellular structure formed by evolving gas during manufacturing. It doesn't need constant vacuum jackets. It generally provides a bridge to heat conduction due to their low density. Furthermore, foam inhibits convective heat transfer by limiting convection to the individual cells, fissures, or other spaces within the foam structure. Foam insulation generally includes some of the moisture barrier, allowed to accumulate within the spacers of the foam the thermal conductivity rapidly increases. Typical foam insulation consists of polyurethane foam, polyamide foam, and foam glass. Polyurethane is a family of polymers or plastic. It is a solid and open cellular structure and also flexible or rigid. Foam insulation is generally not favored in cryogenic applications. Such insulation is likely to crack due to thermal cycling and environmental exposure. Crack permit incursions or a sudden attack of moisture and humid air that will form ice and greatly increase the surface area for heat transfer.

Table 3: Thermal Conductivity of Foam Material

Apparent Mean Thermal Conductivity of Some Selected Foams				
Foam	Density (g/cm ³)	Boundary Temperature (K)	Test Space Pressure	Conductivity [μW/(cm K)]
Polystyrene	0.039	300,77	1 atm	330
	0.046	300,77	1 atm	260
	0.046	77,20	10 ⁻⁵ mm Hg	81
Epoxy resin	0.080	300,77	1 atm	330
	0.080	300,77	10 ⁻² mm Hg	168
	0.080	300,77	4 × 10 ⁻³ mm Hg	130
Polyurethane	0.08 - 0.14	300,77	1 atm	330
			10 ⁻³ mm Hg	120
Rupper	0.08	300,77	1 atm	360
Silica	0.16	300,77	1 atm	550
Glass	0.14	300,77	1 atm	350

ANALYTICAL MODEL

The foam/VDMLI combination model is considered as five segments. The first segment consists of the foam layer. The second, third, fourth and fifth segments represent four MLI segments with different densities and spacer material with a vacuum. The model consists of thermal radiation between shields, gas conduction, and solid conduction through the layer spacer materials. The layer densities and no. of shield for MLI segments 5, 8, 15, 18 layers/cm, and 4, 6, 12, 14

shields, respectively. Finally, the last segment is considered as the shroud. MLI layers to avoid the radiation blockages within the layers and efficient performance of MLI. The thermal conductivity of foam (polyurethane) is 0.033 W/M.K and thermal conductivity of MLI is $1.4 \times \text{W/Mk}$. The cost of the insulation should be minimum and heat transfer rate should be minimum.

Foam/VDML

The cold temperature at the interior of the foam and hot temperature at the exterior of the shroud it determines the cryogenic liquid and the environment. Here the cold temperature of 77 K and hot temperature of 310 K .

Figure 3: Electrical Analogy of Composite Wall

$$Q = \frac{(\Delta T)_{\text{OVER ALL}}}{R_{\text{TOTAL}}} = \frac{T_1 - T_6}{R_{\text{conv1}} + R_1 + R_2 + R_3 + R_4 + R_5 + R_{\text{conv2}}} \text{ Watts}$$

$$U_{\text{Over all heat transfer coefficient}} = \frac{1}{R_{\text{total}} \cdot A} \quad (\text{m}^2 \cdot \text{k/W})^{-1}$$

$$R_{\text{conv1}} = 1/h_1 A, \quad R_{\text{conv2}} = 1/h_2 A$$

$$R_{\text{total}} \text{ is } \text{m}^2 \cdot \text{k/W}$$

$$\text{Therefore, } \frac{\Delta x}{K \cdot A} = \text{resistance}$$

Δx or L is the thickness of the wall

K is the thermal conductivity of the composite material.

$$h_1, h_2 \text{ is } \text{W/m}^2 \cdot \text{k}$$

A is cross section area is considered as unit surface area.

Film Coefficient

Table 4: Conventional Values

Free Convection	Gases: 2-25
	Liquid: 50-100
Forced	Gases: 2-250
	Liquid: 50-20,000
Boiling/Condensation	2500-100,000
Typical Values of h ($\text{W/m}^2 \cdot \text{K}$)	

Composite Wall or FOAM/VDMLI Schematics

Figure 4: Full View of VDMLI Segments

The model was divided into segments. In each segment have to insert the spacer material. The main motto of the design is the cost of the insulation should be minimum and also heat transfer rate should be minimum. Here T_2, T_3, T_4, T_5 is interface temperatures.

Heat Transfer through Composite Wall

Considering five layers of different material thickness $\Delta x_1, \Delta x_2, \Delta x_3, \Delta x_4, \Delta x_5$. With thermal conductivities k_1, k_2, k_3, k_4, k_5 respectively. The heat transfer passing through the 1st layer is the same as that passing through another layer and coming-out finally.

Interface temperature

$$Q_{1st \text{ layer}} = -k A (T_1 - T_2) / \Delta x_1$$

$$(T_1 - T_2) = -\Delta x_1 . Q / K_1 . A$$

$$Q_{2nd \text{ layer}} = -K A (T_2 - T_3) / \Delta x_2$$

$$(T_2 - T_3) = -\Delta x_2 . Q / K_2 . A$$

$$Q_{3rd \text{ layer}} = -K A (T_3 - T_4) / \Delta x_3$$

$$(T_3 - T_4) = -\Delta x_3 . Q / K_3 . A$$

$$Q_{4th \text{ layer}} = -K A (T_4 - T_5) / \Delta x_4$$

$$(T_4 - T_5) = -\Delta x_4 . Q / K_4 . A$$

$$Q_{5th \text{ layer}} = -K A (T_5 - T_6) / \Delta x_5$$

$$(T_5 - T_6) = -\Delta x_5 . Q / K_5 . A$$

Design was done in ANSYS

Figure 5: Segments Designed in Ansys stp File

Foam is a solid material segment and remaining 4 MLI segments are shown in 4 colors. Here the spacers are point contact spacers (SCREEN BETWEEN SHIELDS). In the spacers, the empty space is vacuum, its pressure should be below $7.5 \times \text{Torr}$.

Figure 6: Screens between Shields

Figure 7: Spheres between Shields

Figure 8: Point Contact between Shields

The above two designs are used in MLI layers, it consists of knots which are attached to a fine segment in each design, the empty space was considered as vacuum below 7.5×10^{-5} torr. In both designs, the knots attached as point contact due this arrangement meshing is not generating between knots and the fine segments.

Meshing of the segments is shown in the below images

Meshing is a curvature and approximate mesh was done

Figure 9: Meshing

Figure 10: Meshing Segments

Internal Temperatures of the VDMLI

TABLE 5: Internal Temperatures

Layers	Temperature
Foam	77k
MLI	288.8k
MLI	292.4k
MLI	297 k
MLI	310 k

RESULTS

Temperatures of the internal segments are varying between 77k to 310 k. The internal temperature is maximum at 3rd MLI segment with 292.4 k.

Foam is used to reduce the heat conduction and Multilayer insulation with vacuum is used to avoid radiation with the help of radiation shields. Inside the insulation temperature is decreasing and the system may lead to good efficiency.

CONCLUSIONS

The present investigation report that internal temperatures of the VDMLI is maxed heat transfer rate and no.of shields increases in each segment and cryogenic insulation concepts.

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