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Thermal performance of multilayer insulation: A review

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Abstract: A multilayer insulation (MLI) is a passive thermal protection system used in cryogenics and space exploration programs as a thermal insulator. It is very thin and light weight. Due to less weight and higher thermal performance of MLI, it found application in space programs to store cryogenic liquid propellant. The effective thermal conductivity of MLI is in the order of 10^{-5} W/mK. The prediction of heat transfer in MLI is very complex due to the anisotropic conductivity and combination of radiation, gas conduction and solid conduction modes of heat transfer. This work is an attempt to gather some significant research outcome in MLI performance prediction and the factors to be considered while modeling the MLI.

Key words: multilayer insulation, thermal protection system, thermal control

1. Introduction

MLI was introduced in 1950's. It consist of multiple foils made of Kapton or Mylar coated with a highly reflective metal placed parallel to each other and low thermal conductive spacers are arranged in between the foils to avoid direct contact with the foils[1]. Radiation, solid conduction and gas conduction are the significant modes of heat transfer in MLI. Multilayer insulations are capable of maintaining hundreds of temperature gradient across a thin insulation. The effective thickness of a typical MLI is within few millimeters. MLI found application in storage of cryogenic fluids storage used for space missions as propellant. It is also used in MRI scanning systems to produce high intensity magnetic fields with the help of superconductivity. It also known as a passive thermal control system used in satellites to maintain the temperature of electronic equipment within the working temperature limit.

The radiation heat from the outer space strikes on the first reflective layer where a part is reflected back to the environment, and the remaining radiation energy heats up the first layer of spacer. As the temperature of the layer increases, solid conduction, gas conduction and radiation takes place through the spacer material to the next foil. Thus the second foil temperature will increase. The second foil reflects some radiation back to the first foil and the remaining energy transfers to the third foil. This process continues up to the bottom layer.

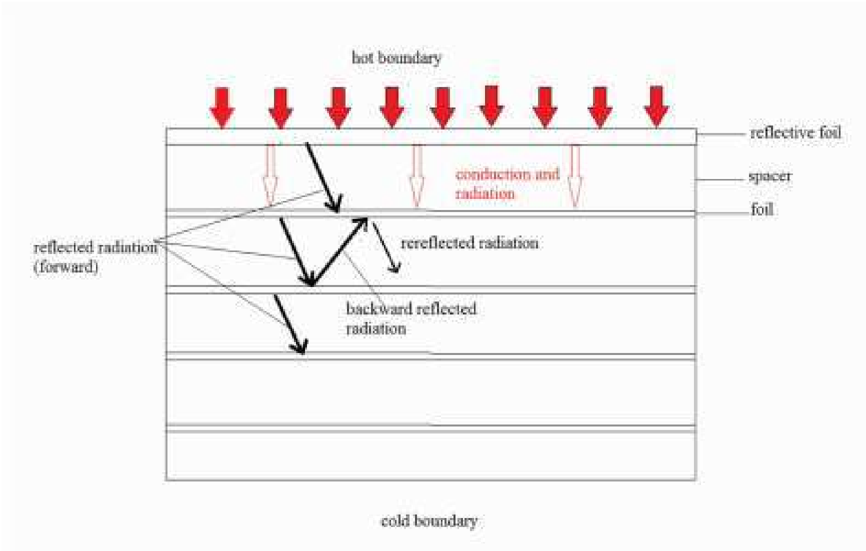

Figure 1. Schematic of MLI

2. Developments in MLI

In the area of multilayer thermal insulation, large quantity of investigation result is generated over the last few decades. Experimental, numerical as well as combined work is being carried out with probable statistics as given in Figure 1. This work is an attempt to review the research progress in the performance of multilayer thermal insulation.

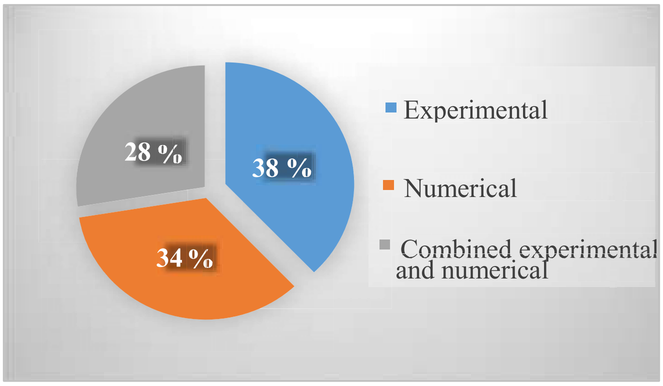

Figure 2. Chart demonstrating the literature

2.1 Experimental investigations

Bapat *et al* [3] conducted an experimental investigation in different combinations of spacer and shield material and compared with numerical model. The result shows that the combination of aluminized Mylar of 12µm thick and glass fabric of 76.2µm thick is the best for MLI. Wei *et al* [8] experimentally investigated the effect of structure and shape of perforated MLI blanket. A new calorimeter with spherical top and bottom is compared with a cylindrical calorimeter and found that 13% excess heat flux is transferred in new calorimeter. It is due to the "edge effect" formed by deformation of MLI. Thus it is concluded that shape and structure will affect the performance of MLI. A steady state experimental investigation is carried out by Sun *et al* [9] to measure the effect of interstitial gas pressure (degraded vacuum). In this experiment argon, air, nitrogen and carbon-dioxide are used as the interstitial gas. The experiment is carried out at different heat transfer condition ranging from free molecular to continuum regime with gas pressure ranges from 10^{-3}-10^{5} Pa by using a nitrogen boil-off instrument. The temperature is also varied from 77K to 300K. The energy accommodation coefficient (EAC) introduced by Kogan is the energy exchange between gas and surface which depends on the factors such as surface roughness, gas properties etc. It is calculated for the test gas. Result reveals that the apparent thermal conductivity will be higher at the hot boundary region than the cold boundary and this increase with increase in magnitude of vacuum.

Wesley [13] tested several MLI specimens to find the optimal layer density in Kennedy space Centre, NASA. But the experimental result shows an increase in layer density than the numerical prediction. It is due to the predominance of radiation which is avoided in the model. It is also suggested to use lower layer density for mass and heat load optimization. Heat pipes (HP) are also used in the thermal control system of spacecraft and satellites. They are used to dissipate the heat generated in the satellite electronic components [12]. Taig *et al* [14] used a phase change Material along with heat pipe to enhance the heat transfer rate from the internal components of satellites.

Thomas *et al* [17] used a calorimeter cryostat which is capable of measuring MLI performance at different temperatures. The low temperature cryogenic fluid (LHe) is passed through the test cylinder and the specimen wrapped around it. Thermal performance of high vacuum multilayer insulation (HVMLI) reduces due the leakage of fluid stored in the tank (hydrogen gas is considered). Small amount of nitrogen and oxygen present in between the layers affect the effectiveness of insulation. Getters are used in such case to absorb the gas present in HVMLI. Jian *et al* [23] compared a composite getter of CuO & C with usually used materials to absorb H_2 gas. It is found that CuO & C getter is a cost effective way of absorbing H_2 gas.

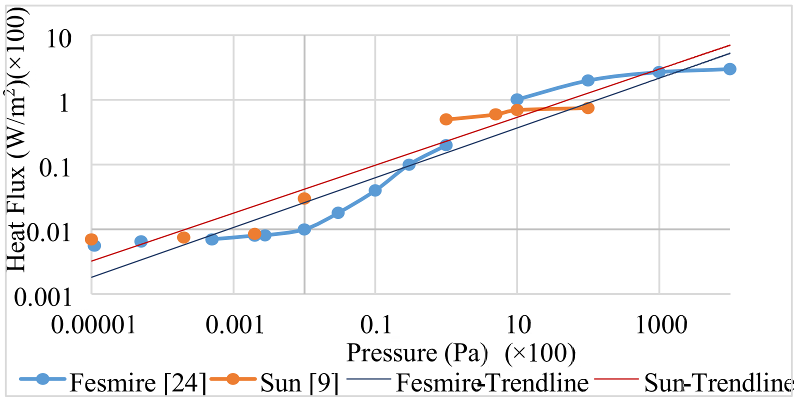

Figure 3. Comparison of heat flux variation with temperature (Sun's [9] and Fesmire's [24] data) and their trend lines.

Fesmire [24] developed a layered composite with aerogel for insulation of non-vacuum application such as space vehicles, propulsion test stand and launch pad and for cryogenic fluid transportation in Kennedy space center, NASA. Johnson *et al* [29] tested the transmissivity of MLI at very low temperature (2K) by using a laser based measuring system. The laser system directly measure the transmittance of MLI and emmitance of aluminium single layer foil. It is found that there is no transmittance of energy through the foil corresponds to 2K. A cylindrical calorimeter is used by Fesmire *et al* [30] to test six different type of MLI. Conclusion is that different combination of MLI is available and the selection of best MLI depends on the application and design of MLI. Table 1 shows a brief idea of experimental investigations in MLI.

Table 1. Experimental investigators in MLI

Author	Parameter analyzed	MLI material	Comments
Bapat [3]	Number of layers and layer density	Few indigenous materials	Thermal conductivity of MLI increases with increase in layer number
Wei [8]	Shape and structure	Double-face aluminum-coated terylene film with fiber paper spacer	Edge effect caused by shape and size leads to reduction in performance of MLI
Sun [9]	Degradation of air	Aluminized Mylar foil with vegetal super-thin fibrous spacer	The effective thermal conductivity increases with temperature and vacuum level
Johnson [13]	Optimal layer density	~	Low layer density will be suitable for thermal and mechanical load optimization.
Thomas [17]	Performance at different temperatures	Double aluminized Mylar with Polyester spacer	Heat load is calculated at different time intervals
Wang [23]	Getters	~	CuO & C is the cost effective getter
Johnson [29]	Transmissivity of MLI	Aluminium single layer foil	Three is no energy transmission through MLI at 2K

2.2 Numerical investigations

Bapat *et al* [2] formulated a numerical model with combined conduction, radiation and gas conduction to predict the performance of MLI with double aluminized Mylar reflective foil and glass fabric spacer. The gas conduction increased with increase in layer density due to the increase in effective thermal conductivity of the insulation.

McIntosh [4] developed a general equation for optimizing heat flux through MLI using a computer program. He used helium as the interstitial gas having a pressure of 1.33E-5 Pa. The radiation heat transfer though MLI is given by

$$Q/A = \sigma\,(T_w^4 - T_c^4)/(1/\varepsilon_w + 1/\varepsilon_c - 1)$$

Where, σ = Stephan-Boltzmann constant = 5.675E(-8) $W/m^2{\cdot}K^4$

T_w = temperature of the warm surface, K

T_c = temperature of the cold surface, K

ε_w & ε_c are the warm and cold surface emissivities

The gas conduction equation is given by

$$H = C_1\ P\ \alpha\,(T_w - T_c)$$

$$k_g = C_1\,P\,\alpha$$

Where, k_g = gas conduction, $W/m^2{\cdot}K$

P = gas pressure, Pa

$C_1 = [(\gamma + 1)/(\gamma - 1)].[R/8\pi.M.T]^{1/2}$

α= accommodation coefficient

$\gamma = C_p/C_v$

R = gas constant, 8.31441 J/mol·K

M = molecular weight of gas, kg/mol

T = temperature of vacuum gauge, normally 300 K

The solid conduction equation is given by

$$k_s = C_2\, f\, k / \Delta X$$

k_s = the solid conductivity per unit thickness, $W/m^2 \cdot K$

C_2 = an empirical constant

f = relative density of the separator compared to solid material

k = separator material thermal conductivity, W/mK

ΔX = actual thickness of separator between reflectors, m

These equations are capable of predicting the performance of MLI with a variety of materials by using a computer application like Microsoft Excel. The result concluded that higher layer density near the warm layer can create better performance.

Alifanov *et al* [10] calculated the thermal and radiative properties such as thermal conductance and emissivity by measuring the temperature and heat flux by inverse problem method. Mavromatidis *et al* [11] studied the effect of air gaps between wall and MLI. The test MLI is placed between two wooden walls maintaining a small gap. It is found that the thermal resistance is maximum when the air gap is 3cm. Gongan *et al* [16] designed a 3D model of lightweight thermal protection system (TPS). A corrugated core sandwiched panel is generated using ANSYS and is subjected to mechanical and thermal loads by using ANSYS parametric design language (APDL) codes. The APDL along with GCMMA algorithm is used for the optimization of minimum weight TPS. 37% lighter TPS is obtained after optimization. But the mechanical loads such as transverse load and in-plane mechanical compressive loads are not considered in the optimization procedure.

Table 2. Numerical investigators in MLI

Author	Model	Comments
Bapat [2]	Combined conduction, radiation and gas conduction	The gas conduction will increases with increase in layer density
McIntosh [4]	Conduction, radiation and gas conduction	The equation can be used for optimization by using a computer program
Alifanov [10]	Inverse problem method	Calculated the properties of MLI
Gongan [16]	3D model of lightweight thermal protection system	37% lighter TPS is created through optimization by APDL & GCMMA algorithm
Tigwu [20]	Conduction, radiation and gas conduction	Calculated 2D temperature distribution inside MLI. Increase in number of layer will increase the performance of MLI up to a limit.
Dye [22]	Discrete spacer	Low area to length ratio spacer reduces conduction heat transfer
Zhan[25]	Quasi steady state	Compared MLI and foam insulation
Xie [26]	Transient heat transfer	MLI with phase change material will increase its performance

Tingwu *et al* [20] numerically investigated the influence of factors such as emissivity, thickness, density layout, location and number of the foils, the density of materials and the emissivity of foils. It has been found that the best performance is achieved at a particular number of layers (18 layers). If the number of layer increases the overall conductivity of the insulation increases due to the domination of highly conductive metallic foils. Dye *et al* [22] designed a wrapped MLI with new discrete spacers having low area to length ratio to reduce the conduction heat transfer.

Zhan *et al* [25] compared the thermal performance of form and MLI in a cryogenic liquid hydrogen tank. Quasi steady state model is used for the analysis process. MLI performance is higher than form at higher temperature where the radiation heat transfer is predominant. The performance of MLI can be improved by introducing the phase change material at the middle layer [26]. But the performance enhancement fails if the phase change material is at the bottom of the insulation.

Paola *et al* [27] developed a design criterion for increasing the effectiveness of multilayered wall insulation for building insulation. Table 2 shows a brief idea of numerical investigation in MLI.

2.3 Combined experimental and numerical investigations

Many researchers used combined numerical simulation and experimental works to verify and improve the accuracy in predicting the performance of MLI.

Krishnaprakas *et al* [5] compared the experimental data of heat flux with four empirical models such as conductance (h-model), effective emittance (ε_{eff}-model), Conduction-radiation (CR-model) and Cunnington and Tien (CT-model). It has been concluded that the CT-model can be used to predict the heat flux accurately. Markus *et al* [6] studied the thermal performance of MLI with porous and fibrous materials which are capable of absorbing, emitting and scattering the radiation. Ohmori [7] introduced a dimensionless contact pressure, P^* in wrapped MLI which is independent of specific weight of foil and radius of cylinder. There is high dependence of MLI performance with the contact pressure.

Table 3. Combined experimental and Numerical investigators in MLI

Author	Numerical	Experimental	Comments
Krishnaprakas [5]	Thermal performance prediction by different models	Heat flux is determined	Cunnington and Tien (CT) model can estimates heat flux accurately
Huang [15]	Finite volume method & inverse problem method	Thermal conductivity is measured	Slight variation between experimental and numerical data
Haim [19]	Conductivity of nitrogen	Thermal conductivity of spacer particle	Contribution of spacer particle in heat transfer is very low

Huang *et al* [15] generated a theoretical model with FVM for analyzing the behavior of high temperature MLI by using inverse problem method. The thermal conductivity of the material is experimentally calculated. The theoretical model shows 4% deviation from the experimental thermal conductivity. Takeshi *et al* [18] developed a new type of small discrete non-interlayer-contact spacer MLI (NICSMLI) made of polyetheretherketone (PEEK) for SPICA satellite. A/L (area to length ratio) of spacer is 10^{-5}m. Haim *et al* [19] tested an annular MLI having stainless steel coaxial foils. 50μm spherical zirconia particle is used as the spacer material which is dispersed in between foils with nitrogen. The overall conductivity of annular MLI shows that the contribution of heat transfer through the particle is very low at vacuum condition.

Nast *et al* [21] tested MLI in large Dewar tanks. A simulation model is presented to measure the cryogenic fluid boil off and thermal conductivity of MLI. The test results are used for designing large propellant tanks for NASA. Wang *et al* [28] tested MLI with Dacron net and fiber cloth as spacer material with different layer density. The heat transfer rate will be comparatively large in fiber cloth than Dacron net due to the higher contact area in the cloth. Table 3 shows significant works of combined experimental and numerical investigation in MLI. Also, Figure 4 portraits the comparison of Nast [21] and Wang [28] data for variation of heat flux with temperature

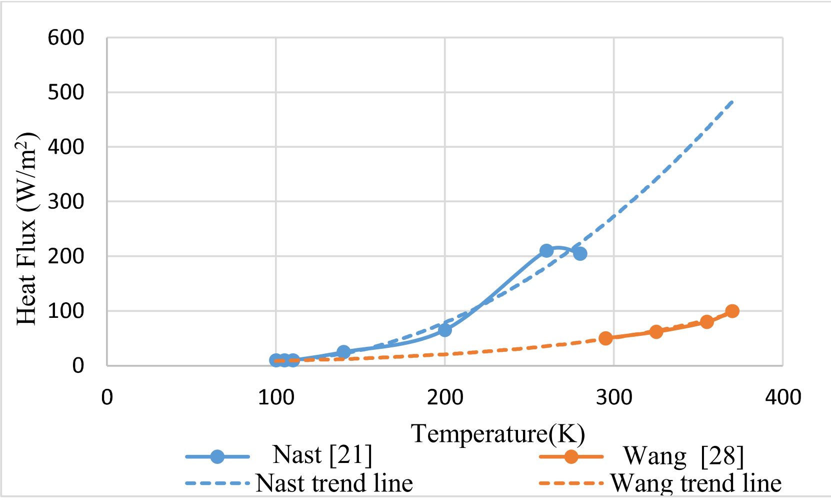

Figure 4. Heat flux variation with temperature (comparison of Nast and Wang data)

3. Conclusions

This review has provided concise summary of investigations on MLI. Based on the studies, MLI is an important insulating material in the field of cryogenic and space industry. The performance prediction of MLI with minimum error is a crucial step in the design of TPS for spacecraft. The performance of MLI is affected by many factors such as contact pressure, boundary temperature, interstitial gas and its pressure etc. Numerical models and simulation software are helpful in analyzing MLI. The experimental method does not match with the exact working condition of MLI in space, but the experimental data can be used to predict the performance of MLI. The use of MLI helps to reduce energy consumption for pumping of heat and heat removal.

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