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Heat transfer analysis of compound multi-layer insulation for cryogenic tank under different service conditions

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Abstract. Future space missions require efficient delivery of large payloads over great distances, necessitating the use of high-energy cryogenic propellant. Therefore, reliable compound multi-layer insulation on cryogenic tank is a crucial part of future space exploration. Compound multi-layer insulation is composed of double-aluminized radiation shielding and separated by a combination of netting and bumper strips， with a foam substrate. Considering conduction, convection, and radiation in heat transfer, the thermal field of multi-layer insulation is analysis by theoretical analysis with different thickness of foam substrate and MLI. Based on the formerly theoretical analysis, the heat flux and apparent thermal conductivity are discussed under the different thickness of foam substrate and MLI. Finally, the optimum design of multi-layer thermal insulation is present in consideration of the thickness and insulation performance of multi-layer insulation.

1. Introduction

Future space programs and missions require efficient delivery of large payloads over great distances. The Cryogenic Fluid Management (CFM) plays a vital role in the development of high-energy upper stage vehicles. Therefore, efficient and reliable insulation materials are a crucial part of future space exploration. The importance of insulation in cryogenics is easily realized by noting that the heat of vaporization of cryogenic liquids, as well as, their specific heats are small, and it takes small amount of heat flux to boil off the cryogenic liquids or to raise the system temperature.

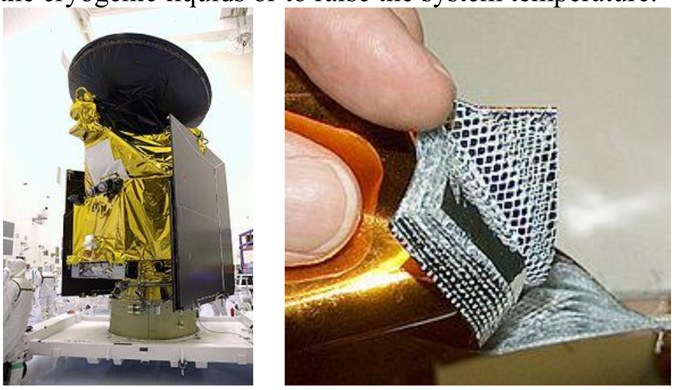

Fig 1 space application of compound multilayer insulation

Multi-layer insulations (MLI) are typically high-vacuum systems made of many radiation shields between the hot and cold boundaries. They normally consist of an assembly of numerous thin plastic films coated on one or both sides by a thin-deposited layer of high reflectance metal, usually aluminium or gold. The multilayer insulation systems can be used in both high-temperature and cryogenic applications, however, the insulation material, the arrangement, and heat transfer characteristics are quite different.

Many groups studied the effects of layer density on MLI throughout the years preceding and following Dr. McIntosh's innovation. The subject of variable density multilayer insulation (VD-MLI) was pioneered by McIntosh in the early 1990's. The theory behind variable density MLI is that since there is an optimal density for MLI as a function of both boundary temperatures, a more optimal solution exists if the MLI system is split into multiple sections or segments. Hyde, Stuckey, Fredrickson, and Spradley have each shown analytically based graphs that suggest the optimal layer density for different systems.

The foam-MLI system performed exceptionally well in the orbit hold testing when compared with historical data and predictions based on constant density MLI concepts. Therefore, the focus in this paper is on analytical modeling of the MLI performance during orbital coast periods.

2. Theory analysis

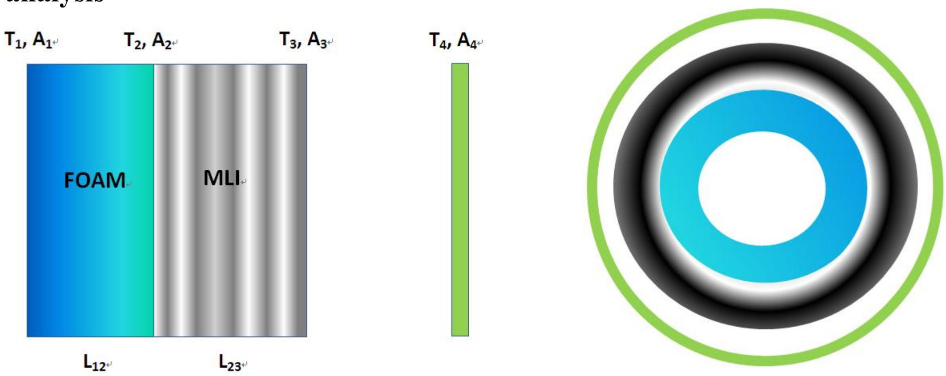

Fig 2 thermal transfer in compound multilayer insulation

To evaluate MLI performance, analytical models is presented. The analytical modeling of the insulation during orbital coast periods is discussed in subsequent sections.

2.1. *Foam conduction* Q_1

The conduction of the foam obeys Fourier's law

$$Q_1 = K_1 A_{12} \frac{T_2 - T_1}{L_{12}}$$

Where, K_1 is foam conductivity(W/m-K), A_{12} is effective area, $A_{12} = (A_2 - A_1)/\ln(A_2/A_1)$.

2.2. *Thermal radiation between MLI* Q_2

The thermal of radiation between MLI can represent:

$$Q_2 = K_r A_{23} \frac{T_3 - T_2}{L_{23}}$$

Where, A_{23} is effective area, $A_{23} = (A_3 - A_2)/\ln(A_3/A_2), K_r$ is MLI apparent conductivity

$$K_r = \frac{1}{N} \frac{\sigma\left(T_1 + T_2\right)\left(T_1^2 + T_2^2\right)}{\frac{(\alpha + 2\gamma)\delta_s}{2n} + \frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1}$$

Where, n is the numbers of shield, N is the density of MLI, $N = n/\delta_s$, ε_1 and ε_2 are the emissivities of the two faces on the shield, δ_s is the thickness of the spacer, α is the absorptance, γ is the transmittance.

2.3. *Thermal transform in vacuum environment* Q_3

Thermal transform in vacuum accounts for two modes of heat transfer: gas conduction and thermal radiation in vacuum, $Q_3 = Q_{fm} + Q_r$.

2.3.1. *Gas conduction in vacuum environment.* For the low pressure/vacuum environment, the space between the shields is considered to be in free-molecule regime; therefore, the gas conduction equation is applied,

$$Q_{fm} = KA_3\alpha P\left(T_4 - T_3\right)$$

Where, P is gas pressure, Pa,, α is accommodation coefficient,

$$K = \frac{\gamma + 1}{\gamma - 1}\sqrt{\frac{R}{8\pi MT}}$$

Where, γ is specific heat ratio, R is gas constant, 8.314 kJ/mol-K, M is molecular weight of gas, kg/mol

2.3.2. *Thermal radiation in vacuum environment.* The radiation heat transfer is,

$$Q_r = \sigma\varepsilon_{4-3}A_4\left(T_4^4 - T_3^4\right)\varphi_{34}$$

Where, σ represents Stephan-Boltzmann constant (5.675 E-8 W/m2-K4), φ_{34} is angle factor , ε_{4-3} is comprehensive emissivity

$$\varepsilon_{4-3} = \frac{1}{\frac{1}{\varepsilon_4} + \frac{A_4}{A_3}\left(\frac{1}{\varepsilon_3} - 1\right)}$$

3. Result

Based on the conservation laws of energy, the relation of thermal transfer is

$$Q_1 = Q_2 = Q_3$$

Then equation can be rearrange as

$$\begin{cases} K_1A_{12}\dfrac{T_2 - T_1}{L_{12}} = K_rA_{23}\dfrac{T_3 - T_2}{L_{23}} \\ K_1A_{12}\dfrac{T_2 - T_1}{L_{12}} = KA_3\alpha P\left(T_4 - T_3\right) + \sigma\varepsilon_{4-3}A_4\left(T_4^4 - T_3^4\right)\varphi_{34} \end{cases}$$

When the T_1 =90K, T_4 =293K and P =0.001Pa, from the formerly theoretical analysis, the heat flux is discussed under the different thickness of foam substrate and MLI.

Table 1 the heat flux under the different thickness of compound MLI.

No.	FOAM+MLI	Thermal leakage/W
1	1cm+5cm	0.0324
2	1.5cm+4.5cm	0.0612
3	2cm+4cm	0.1049
4	2.5cm+3.5cm	0.1736
5	3cm+3cm	0.2867

4. Conclusion
In conclusion, the analytical model can be utilized in multiple applications to predict the performance of the SOFI/ MLI combination. In the higher vacuum, compound multi-layer leak lower thermal for the same thickness when it contain more shields. But the foam insulation not only enabled the elimination of a helium purge system, but also reduced the ground hold heat leak sufficiently to improve the effective as compared with an "MLI" only concept.

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