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Research paper

Optimization of variable density multilayer insulation for cryogenic application and experimental validation

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ABSTRACT

Cryogenic propellant storage on orbit is a crucial part of future space exploration. Efficient and reliable thermal insulation is one of the dominant technologies for the long-duration missions. This paper presents theoretical and experimental investigation on the thermal performance of variable density multilayer insulation (VDMLI) with different configurations and spacers. A practical method for optimizing the configuration of VDMLI was proposed by iteratively predicting the internal temperature profiles and maximizing the thermal resistance based on the basic layer by layer model. A cryogen boil-off calorimeter system was designed and fabricated to measure the temperature profile and effective heat transfer coefficient of the VDMLI samples over a wide range of temperature (77–353 K). The experimental data confirm that the optimized sample as predicted does have the minimum effective heat transfer coefficient in the control group. The results indicated that the insulation performance of MLI could be improved by 45.5% after replacing the regular uniform configuration with the optimized variable density configuration. For the same optimized configuration, the performance was further improved by 54% by changing the spacing material from none-woven fiber cloth to Dacron net. It was also found that the effective heat transfer coefficient will be much less sensitive to the MLI thickness when it exceeds 30 mm for on-orbit thermal environment.

1. Introduction

Multilayer insulation (MLI) blanket, composed of low emission rate radiation shields and low-conductivity spacers, has been widely used in cryogenic systems for its super insulation performance as well as lightweight and little pollution. It is regarded as one of the most effective passive thermal control means for cryogenic propellant storage during long duration missions [1] thanks to the existing high vacuum in space. Plenty of theoretical and experimental studies on MLI had been carried out in literature. For example, Krishnaprakas et al. [2] proposed four different empirical models by fitting experimental data of various configurations, which estimated heat flux sufficiently accurate for spacecraft MLI design purposes. Chen et al. [3] developed a heat transfer model to predict the heat flux through uniform density multilayer insulation (UDMLI) thermal resistance at either high or low temperatures. The errors between the predictions and experimental data are less than 10%. Li et al. [4] developed a model for the purpose of calculating the temperature field and inner radiation within the multilayer perforated insulation material, and of evaluating the effect of layer density, screen emissivity, and perforation coefficient on the thermal performance of UDMLI. A method for optimizing layer densities of uniform density MLI was proposed by Johnson [5], which could be used to determine the corresponding optimal thickness of MLI. An analytical modelling of the Variable Density MLI (VDMLI) for on-orbit application was conducted by Hedayat et al. [6], who considered the MLI implemented in three MLI segments with density of 8, 12 and 16 layers/cm, respectively. For a given cold boundary temperature, the prediction error of their model grows with the increasing of the warm boundary temperature, from 5% at 310 K to 34% at 170 K. Most of the models on MLI adopted uniform density distribution although some of which involved with the influence by the layer density. Although the VDMLI model was employed to predict the heat flux through the VDMLI, the optimization method for variable density configuration wasn't proposed.

Regarding experimental research, Johnson et al. [7,8] studied the thermal performance of the UDMLI at various layer spacings. It was found that the optimal layer density for two-ends' boundary temperatures of 77 K and 305 K respectively was approximately 26 layers/cm. Fesmire et al. [9–11] studied the thermal performance

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Nomenclature

CBT	cold boundary temperature (K)
DAM	double-aluminized mylar
D_i, D_o	inner and outer diameters (m)
D_x	actual thickness of spacer between reflectors (m)
f	relative density of the spacer
h_{fg}	latent heat of liquid nitrogen (J/kg)
λ	the thermal conductivity of spacer material (W/(m·K))
K_{eff}	effective heat transfer coefficient
K_r	radiation heat transfer coefficient
K_g	gas conduction coefficient
K_s	solid conduction coefficient
K_T	the total conductance between any two adjacent layers (W/(m·K))
m	the number of radiation spacers
MLI	multilayer insulation
M	molecular weight of gas (g/mol)
N	total number of layers
n	the number of radiation shields
p	gas pressure (kPa)
q_{tot}	heat flux through the MLI (W/m^2)
q_{rad}	thermal radiation between shields (W/m^2)
q_{g_cond}	gas conduction (W/m^2)
q_{s_cond}	solid conduction (W/m^2)
R	gas constant = 8.314 J/(mol·K)
R_T	the thermal resistance of MLI
R_i	resistance between layer i-1 and layer i
S1, 2, 3	segment 1, 2, 3
T_c	temperature of the cold surface (K)
T_H	temperature of the warm surface (K)
ΔT	temperature difference between cold and warm boundary temperature (K)
UD	uniform density
V	volume flow rate (m^3/s)
VD	variable density
WBT	warm boundary temperature (K)
σ	Stefan–Boltzmann coefficient W/(m^2·K^4)
ε_c	emissivity of the cold surface
ε_H	emissivity of the warm surface
α	accommodation coefficient
ρ	density of the nitrogen vapor (kg/m^3)

of UDMLI conducted in large scale cryogenic facilities. At a high vacuum level, the thermal conductivity of the MLI was about 0.09–0.16 mW·m^{-1}·K^{-1} at the boundary temperature of 78 K and 293 K. Hastings and Hedayat et al. [12] evaluated the insulation performance of VDMLI in Multipurpose Hydrogen Test Bed by ground-hold tests, ascent flight simulations, and orbit-hold simulations. The heat flux through VDMLI at the two-end's boundary temperature of 21 K and 235 K was about 0.18 W/m^2 in high vacuum. Zia et al. [13] devised several methods for creating variable density in MLI, including adding more spacer layers, adding bumper strips of spacer material and embossing the spacer material. Results showed that the bumper strips and embossed spacer design reduced the heat flux of 9.4% and 5.8%, respectively. Hastings et al. [14] evaluated the performance of a compound insulation with foam and variable density multilayer in the Multipurpose Hydrogen Test Bed. The orbit hold simulation produced a heat leak of 0.22 W/m^2 at warm boundary temperature of 305 K, which means a 50% heat leak reduction. Spacing materials also have significant effect on the VDMLI performance. These studies on VDMLI have shown that varying density intentionally can further reduce the overall weight and radiation losses compared to the uniform density, which is attractive to the applications prospected in long term storage of cryogenic propellant on orbit. Adoption of different spacing material/structure and optimization of the thickness of MLI are focusing issues in this area in recent years. Johnson et al. [15] tested the thermal performance of the MLI with silk net spacer over the temperature range of 78–325 K. The results showed that the MLI with silk net had a dramatically lower heat load and a minimally lower mass than polyester net and fiberglass paper. Ohmori et al. [16] investigated the effect of thickness on the thermal performance of MLI. The heat flux through the MLI with different layer density and thickness were evaluated experimentally. The data showed better insulation performance of the MLI which employed 6 μm thick polyester film.

This study intends to propose a practical method for guiding the variable density configuration of MLI for optimal performance, and to verify the optimization results through experiments. The effects of layer density, spacing materials and thickness on the thermal performance of VDMLI will be discussed.

2. Theoretical model and implementation

2.1. Layer by layer model

The "layer by layer" model shown in Fig. 1 is adopted for predicting the temperature profile and heat flux through the MLI, based on a methodology proposed by McIntosh [17]. This model takes into account three modes of heat transfer: the thermal radiation between the shields q_{rad}, the residual gas conduction q_{g_cond}, and the solid conduction q_{s_cond} through the spacers. The total heat flux through the MLI q_{tot} is given by

$$q_{tot} = q_{rad} + q_{g\_cond} + q_{s\_cond} \tag{1}$$

The radiation heat transfer is written as

$$q_{rad} = K_r(T_H - T_c) \tag{2}$$

where K_r is the radiation heat transfer coefficient

$$K_r = [\sigma(T_H + T_c)(T_H^2 + T_c^2)] \Big/ \left(\frac{1}{\varepsilon_H} + \frac{1}{\varepsilon_c} - 1\right) \tag{3}$$

and the Stefan–Boltzmann coefficient $\sigma = 5.67 \times 10^{-8}$ W/(m^2·K^4), T_H and T_c are the temperatures (in K) of the warm surface and cold surface, respectively. ε_H and ε_c are the emissivity of the warm surface and cold surface, respectively, both taking 0.04 for aluminized shield.

The gas conduction part could be written as:

$$q_{g\_cond} = K_g(T_H - T_c) \tag{4}$$

$$K_g = C_1 p \alpha \tag{5}$$

$$C_1 = \left[\frac{\gamma + 1}{\gamma - 1}\right][R/8\pi M T]^{1/2} \tag{6}$$

where p is the residual gas pressure, α is the accommodation coefficient (0.9 for air), R is the general gas constant = 8.314 J/(mol·K), M is the molecular weight of gas (g/mol), and T is the temperature of the vacuum chamber wall (K). $\gamma = c_p/c_v$, where c_p is isobaric heat capacity, and c_v is isochoric heat capacity (kJ/(kg·K)). Then for air and the vacuum chamber at room temperature, C_1 = 1.1666.