Proceedings of the 8th World Congress on Mechanical, Chemical, and Material Engineering (MCM'22)
Prague, Czech Republic – July 31, 2022 - August 02, 2022
Paper No. HTFF 160
DOI: 10.11159/htff22.160

Heat Flux Prediction Accuracy Assessment of Separated Mode and Doenecke Equations for MLI Blankets

Toygan Er[1,2], Özgür Ekici[3]
[1]Turkish Aerospace Industries, Inc
Fethiye Mahallesi, Havacılık Bulvarı No:17 06980 Kahramankazan Ankara, Turkey
[2]Hacettepe University
Hacettepe University Faculty of Engineering, Department of Mechanical Engineering, Beytepe, Ankara, Turkey
toygan.er@tai.com.tr; ozgur.ekici@hacettepe.edu.tr
[3]Hacettepe University
Hacettepe University Faculty of Engineering, Department of Mechanical Engineering, Beytepe, Ankara, Turkey

Abstract – Assessment of thermal performance of Multilayer Insulation (MLI) blankets is necessary to achieve thermal design criteria of the spacecraft applications where the MLI blankets are massively employed. This assessment can be done by either experimental observations or by the empirical and numerical equations which predicts the heat flux through MLI blankets with limited accuracies. In this paper, two different heat flux prediction equations, Layer by Layer MLI Calculation Using a Separated Mode Equation and Doenecke Equation, were discussed, and the required numerical programming codes for these equations were generated in MATLAB. In addition, an in-house experimental study for two different MLI blankets at 146 K and 198 K cold boundary temperatures was introduced and explained. The experimental setup and the experimental steps were explained. The steady state heat flux results of MLI blankets were used to evaluate the prediction accuracies of discussed equations based on the generated codes. The accuracy of equations was compared with each other and with the experimental data. Based on this study, the heat flux prediction accuracies of separated mode equation and Doenecke equation were calculated to be 13.2% and 7.3% with respect to experimental data for 8 layer MLI blanket sample for 198 K and 146 K cold boundary temperatures. As for 22 layer MLI blanket sample, heat flux prediction accuracies of separated mode equation and Doenecke equation were calculated to be 13.2% and 11.8% with respect to experimental data obtained at the same cold boundary temperatures.

***Keywords*:** MLI blanket, thermal insulation, thermal performance, predictive equations, heat flux

1. Introduction

Spacecraft applications require effective thermal insulation due to the extreme space temperatures which varies between –250°C and +300°C [1]. MLI blankets are the passive thermal insulation materials utilized in spacecraft and satellite applications. MLI blankets are the most effective thermal insulation method in high vacuum environment [2].

MLI blankets consist of multiple alternating reflector shields and spacers. Reflector shields reflect the radiative energy emitted from the environment. Spacers are used between shields to avoid contact between shields to minimize conductive heat transfer through shields. To minimize overall heat transfer, low emissivity and low conductivity materials are used.

In order to meet the thermal design criteria of spacecrafts, accurate thermal performance prediction of MLI blankets has to be made. However, since the abovementioned heat transfer modes of MLI blankets have complex relationship with each other, the calculation of thermal performance of MLI blankets is not straightforward. In literature, different mathematical expressions were created to predict the heat flux through MLI blankets based on some assumptions. Cunnington and Tien [3] created a heat flux prediction equation which calculates the heat transfer through MLI blankets with an accuracy of 20% by using the parameters of the MLI blanket components and the environmental conditions. Keller and Cunnington [4] improved and simplified this equation by replacing some of parameters with empirical constants obtained by set of experimental observations. Various empirical constants were determined for the MLI blankets consisting of a variety reflector shield and spacer materials. Prediction results of this equation were reported to have an accuracy within ±8% with respect to experimental heat flux results. Hedayat et. al. [5] adjusted the existing Lockheed equation to accommodate Dacron spacer material. The created equation was reported to have the accuracy between 8% and 30% for the warm boundary temperature of 305 K and 164 K respectively. McIntosh [6] developed Layer by Layer MLI Calculation Using a Separated Mode Equation which calculates the heat transfer through the MLI blankets layer by layer iteratively. After the iteration process, the heat flux prediction of MLI blanket and the temperature distribution of shields can be obtained. Doenecke [7] investigated many experimental data in the literature and developed an equation for prediction of thermal performance of MLI blankets based on these experimental data. With this equation, heat flux prediction of MLI blankets for spacecraft applications can be calculated for different number of shields, shield perforation and blanket areas.

Literature survey reveals that the predictive accuracies of created equations were validated by experimental data at only limited temperature ranges. Also, since these experimental studies were carried out with limited type of materials, the validity of these equations for different materials are unknown. Therefore, these equations must be validated for extended temperature ranges and different MI blanket materials through experimental studies. In this study, the heat flux characteristics of 8 and 22 layer MLI blankets with same material were discussed at two different cold boundary temperatures with different warm boundary temperatures. Obtained heat flux results were compared with the prediction results of Layer by Layer MLI Calculation Using a Separated Mode Equation and Doenecke Equation.

2. Heat Transfer Calculations

Heat transfer through MLI blankets consist of thermal radiation, solid conduction and at pressurized environment, gaseous conduction. Thermal radiation is inversely proportional with the number of shields used in MLI blankets. Therefore, lower radiation heat leaks can be obtained by using more reflective shield. Due to spacer material between shields, solid conduction exists and can be minimized by lowering the density of the spacer. Also, fluffy structure of MLI blankets helps to increase the thermal contact resistance of spacer material. Gaseous conduction can be minimized by providing perforation holes on shields so that the trapped medium can be evacuated from the perforation holes of the shields.

MLI blankets have a structure consisting of many parallel low emissivity shields. For an MLI blanket, consisting of N number of shields radiative heat rate equation is given in Eq. (1).

$$q_r = \sigma(T_2^4 - T_1^4)\frac{1}{(N-1)(\frac{1}{\varepsilon_1}+\frac{1}{\varepsilon_2}-1)} \tag{1}$$

where q_r is the radiative heat transfer rate σ is the Stefan-Boltzmann constant, ε_1 and ε_2 are the emissivity of the alternating shields and $T_1$and T_2 are the temperature of the alternating surfaces in Kelvin.

In MLI blankets, solid conduction occurs due to the thermal contact between the alternating shields and spacer. The Fourier's law of heat conduction becomes as in Eq. (2) in order to express the solid conduction through MLI blankets due to the netting shape of spacer material and the fluffy structure of MLI blankets.

$$q_c = \frac{C_e\,\mathrm{f}\,k(T_h - T_c)}{\Delta X} \tag{2}$$

where q_c is the conductive heat transfer rate, C_e is an empirical constant related to contact resistance, f is the relative density of the spacer material, k is the conductivity of the spacer material, ΔX is the thickness between each shield layer and T_h and T_c are the warm and cold boundary temperatures respectively.

The gas conduction is independent from the environmental pressure at high pressure levels. The rate of gas conduction is described by Fourier's since the flow is in continuum region [8]. Unlike high pressures, the gas conduction is pressure dependent at high vacuum environment. For high vacuum coaxial cylinders systems, heat rate equation due to gas conduction was obtained by Knudsen [9]. This formulation became useful after Corruccini by rewriting the equation for concentric spheres, coaxial cylinders and parallel plates as in Eq. (3) [10].

$$q_g = \left(\frac{\gamma + 1}{\gamma - 1}\right) \propto \left(\frac{R}{8\pi M T_m}\right)^{\frac{1}{2}} P(T_2 - T_1) \tag{3}$$

where R is the gas constant, P is the environmental pressure, M is the molecular weight of the gas, T_m is the mean temperature, γ is the specific heat ratio, $\propto$ is the overall accommodation factor and T_1 and T_2 are the temperatures of the alternating surfaces. When the constants of Eq. (3) were lumped into a constant C_g and the equation can be simplified as in Eq. (4).

$$q_g = C_g \propto P(T_2 - T_1) \tag{4}$$

3. Experimental Studies

The experimental studies were carried out at GÖKTÜRK-2 Thermal Vacuum Chamber (TVAC) in order to create the vacuum environment required for observing the thermal performance of the MLI blankets experimentally. Two different MLI samples, consisting of 8 and 22 layers of double-sided aluminium coated PET shield with a perforation rate of 0.84% and Dacron B4A netting spacer were used in the experimental studies. Prepared MLI blankets were wrapped around an aluminium block. 4 heaters were installed on the block surface to create a warm temperature boundary at this side of the MLI blanket. To create a cold temperature boundary at the outer side of MLI blanket samples, the thermal shrouds of the TVAC were regulated at 113K and 188K of cold boundary temperatures during the experiments. 21 thermocouples were used to measure the temperatures. 7 thermocouples were used on the aluminium block to measure the warm boundary temperatures. 14 thermocouples were used to measure the cold boundary temperatures on MLI blankets. The thermocouples on the warm and cold boundaries were placed parallel to each other to neglect any lateral heat flux effect through MLI blankets. The thermocouple and heater layout at the block surface and the thermocouple layout at the outer side of MLI blanket is given in Fig. 1. After the preparations on the aluminium block, the samples were hanged inside the TVAC by means of eyebolts using steel rope. The view of TVAC with MLI blanket samples is shown in Fig. 2 [11].

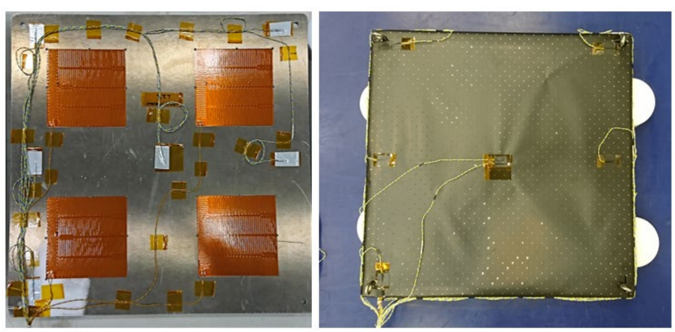

Fig. 1: Thermocouple and heater layout on MLI Samples

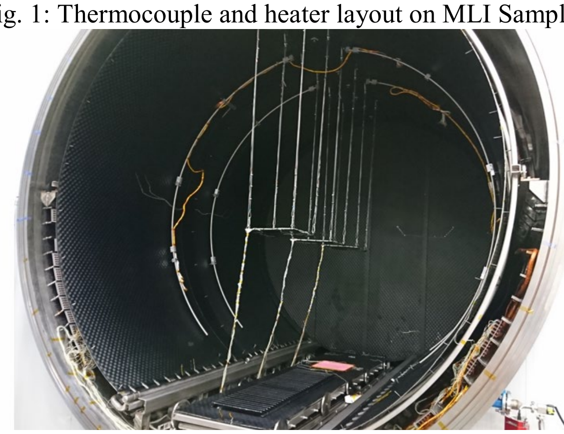

Fig. 2: TVAC with Experimental Setup

At each cold boundary temperatures, 3 different power input were applied to the heaters inside of the MLI samples to create a warm boundary at the inner side of the MLI samples. Therefore, 6 steady state temperature data were recorded for 6 different power inputs. The thermocouples located at the middle of the MLI samples were used in order to calculate the heat flux through MLI blanket samples. Steady state cold and warm boundary temperatures and the applied power at the heaters for both samples were presented in Table 1.

Table 1: Experimental Results of MLI Blanket Samples

Blanket Sample	Case No	Applied Power (W/m^2)	Cold Boundary Temperature (K)	Warm Boundary Temperature (K)
8 Layer	1	4.59	146	254.0
	2	6.02	146	281.0
	3	8.57	146	303.7
	4	3.09	198	265.7
	5	5.95	198	310.9
	6	7.62	198	324.1
22 Layer	1	3.01	146	256.4
	2	4.57	146	289.4
	3	6.80	146	322.2
	4	1.73	198	262.1
	5	4.51	198	323.1
	6	5.68	198	335.8

4. Heat Flux Prediction Equations

4.1. Layer by Layer MLI Calculation Using a Separated Mode Equation

Layer by Layer MLI Calculation Using a Separated Mode Equation is used in order to predict the temperature profile and heat flux through MLI blankets. In this method, the heat transfer through MLI blankets is calculated layer by layer by an iterative manner. After all thermal resistances were calculated for each layer pair, the iteration process continues until heat rates between each layer pairs are equal.

This equation uses Eq. (1), Eq. (2) and Eq. (4) for the heat transfer equations of thermal radiation, solid conduction and gaseous conduction respectively. In order to utilize these equations, some of the parameters of the MLI blanket samples must be determined. In MLI blanket samples, Dacron B4A netting spacer material was used. The solid conductivity of this material was approximated as temperature dependent in [6] as in Eq. (5).

$$k = 0.017 + 7\text{x}10^{-6}(800 - \text{T}) + 0.0228\ln(\text{T}) \tag{5}$$

Spacer density is the ratio of the weight of the spacer to the solid density of the material of the spacer. Since the spacer materials have a void netting structure, the weight of the spacer itself is much less than the solid weight of the material of the spacer material. In order to define the spacer density, image processing tool of MATLAB was used.

Thickness between the shields of the MLI blanket samples is another parameter to be determined. MLI blanket thickness was measured by means of penetrating the MLI blanket samples by a needle probe from different locations as proposed in [12]. The penetrated length of the needle probe was measured with a calibrated vernier caliper. The measured thicknesses were averaged and resulting average thicknesses were accepted to be the thickness of MLI blanket samples

For emissivity of the aluminized shields, Gu [13] defines the aluminium emissivity as a function of temperature as in Eq. (6). Also, in the same study, the empirical constant C_e in the solid conduction equation was modified for a wider range of temperature in between 80 K to 300 K. Equation of C_e is shown in Eq. (7)

$$\varepsilon = 0.011823 + 6.17562x10^{-5}T \tag{6}$$

$$C_e = 0.008(-0.2005673 + 3.2843027)0.011823 + 6.17562x10^{-5}T^2 \tag{7}$$

Gas conduction equation shown in Eq. (4) requires the accommodation factor and the C_g values. These values were defined in [6] as 0.9 and 1.1666 respectively. The required parameters of the heat transfer equations used in Layer by Layer Layer MLI Calculation Using a Separated Mode Equation were tabulated in Table 2.

Table 2: Parameters Used in Layer by Layer MLI Calculation Using a Separated Mode Equation

Parameter	8 Layer MLI Blanket	22 Layer MLI Blanket
Number of Shields (N)	9	23
Shield Emissivity (ε)	Eq. (10)	Eq. (10)
Empirical Spacer Conduction Coefficient (C_e)	Eq. (11)	Eq. (11)
Relative Density (f)	0.1193	0.1193
Layer Thickness (ΔX)	0.000282	0.000202
Spacer Material Conductivity (k_s)	Eq. (9)	Eq. (9)
Interstitial Gas Pressure (P)	$5x10^{-4}$	$5x10^{-4}$
Accommodation Coefficient	0.9	0.9
Empirical Gaseous Conduction Constant (C_g)	1.1666	1.1666

4.2. Doenecke Equation

Doenecke equation was proposed for the prediction of heat transfer through MLI blankets for spacecraft applications. Therefore, the gas conduction is neglected in this equation since the vacuum level in space is very low. This empirical equation was correlated with the heat transfer measurement of various MLI blankets in the literature. The structure of this equation is shown in Eq. (8).

$$\varepsilon_{eff} = (C_S \frac{1}{4\sigma {T_m}^2} + C_R T_m^{0.667}) f_N f_A f_P \tag{8}$$

where ε_{eff} is the effective emissivity of MLI blanket, C_S is the solid conduction constant, C_R is the thermal radiation constant, T_m is the mean temperature, f_N, f_P and f_A is the factor of number of shields, perforation rate and area respectively. In Eq. (8), the performance of MLI blankets is given in terms of effective emissivity. By using Stefan-Boltzmann law, the prediction of heat flux through MLI blankets can be found as shown in Eq. (9).

$$q = (C_S \frac{1}{4\sigma {T_m}^2} + C_R T_m^{0.667}) f_N f_A f_P) \sigma (T_h^4 - T_c^4) \tag{9}$$

WhereT_h and T_c are the warm and cold boundary temperatures of the MLI blanket. In the original research, the C_S and C_R values were given as 0.000136 and 0.000121 respectively. The parameters of f_N, f_P and f_A were also given in Table 3, and Eq. (10) respectively.

Table 3: Correction Factor of f_N and f_P

N	f_N
5	2.048
10	1.425
15	1.164
20	1.000
25	0.905
30	0.841

Perforation Rate (%)	f_P	
	ε=0.04	**ε=0.03**
0.1	0.756	0.704
0.2	0.783	0.737
0.5	0.865	0.837
1.0	1.000	1.000
1.5	1.133	1.161

$$f_A = 1/10^{(0.373\, logA)} \tag{10}$$

Using the tabulated data and the equations, the parameters for the 8 and 22 layer MLI blanket samples were determined. The f_N, f_A and f_P values for MLI blanket samples are presented in Table 4.

Table 4: Parameter Values for MLI Blanket Samples

Parameters	8 Layer MLI Blanket	22 Layer MLI Blanket
f_N	1.6023	0.9530
f_A	0.9491	0.9491
f_P	1.2577	1.2577

4.3. Comparison of Heat Flux Prediction Results with Experimental Data

The parameters determined for both equations in section 4.1 and 4.2 were used in the generated MATLAB code for the Layer by Layer MLI Calculation Using a Separated Mode Equation and Doenecke equation respectively. The codes and the details on the programming process can be further reviewed in [11]. The cold boundary temperatures at the experiments were also used as input in the generated code. The heat flux predictions of both equations were obtained for different warm boundary temperatures. Obtained predictions were compared with the experimental data.

The prediction results of both equations for 8 layer MLI blanket at 198 K and 146 K cold boundary temperatures are shown in Fig. 3. At 198 K cold boundary temperature, the Layer by Layer equation overestimates the heat flux predictions at increasing warm boundary temperatures for 8 layer MLI blanket. However, at 146 K cold boundary temperature, The Doenecke underestimates the heat flux for the 8 layer MLI blanket. The comparison of heat flux results of both equations with respect to experimental data is shown in Table 5 and Table 6.

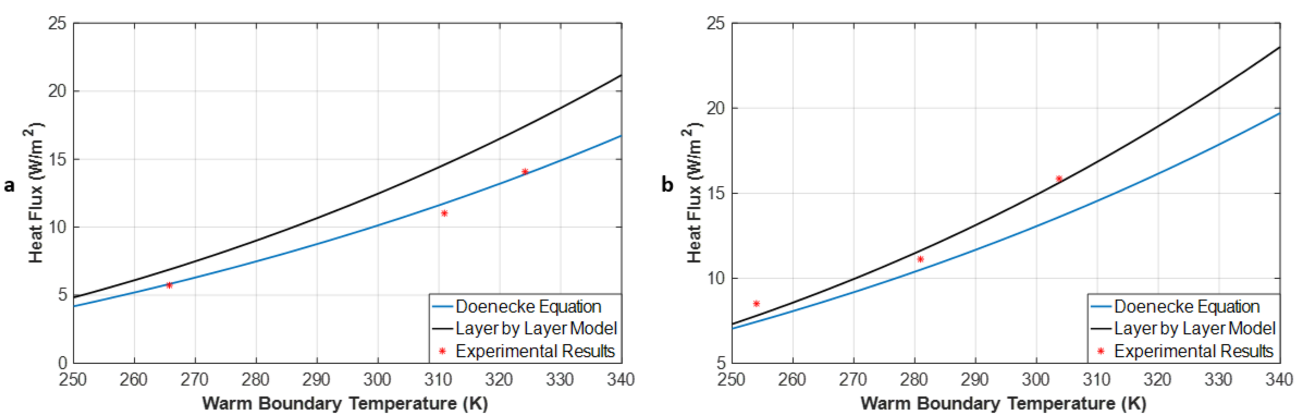

Fig. 3: Experimental and Numerical Results for 8 layer MLI Blanket at 198 K (a) and 146 K (b) Cold Boundary Temperature

Table 5: Heat Flux Results of Investigated Equations for 8 Layer MLI Blanket at 198 K

Warm Boundary Temperature (K)	Layer by Layer Equation Heat Flux (W/m^2)	Doenecke Equation Heat Flux (W/m^2)	Experimental Heat Flux (W/m2)
265.7	6.57	5.88	5.73
310.9	14.25	11.77	11.02
324.1	17.07	13.87	14.09

Table 6: Heat Flux Results of Investigated Equations for 8 Layer MLI Blanket at 146 K

Warm Boundary Temperature (K)	Layer by Layer Equation Heat Flux (W/m^2)	Doenecke Equation Heat Flux (W/m^2)	Experimental Heat Flux (W/m2)
254.0	7.79	7.44	8.504
281.0	11.63	10.51	11.14
303.7	15.64	13.50	15.86

The prediction results of both equations for 22 layer MLI blanket at 198 K and 146 K cold boundary temperatures are shown in Fig. 4. As illustrated, both Doenecke Equation and Layer by Layer equation show good agreement with the experimental data at 198 K cold boundary temperature. At increasing warm boundary temperatures, the prediction results of Layer by Layer equation is slightly better. At 146 K cold boundary temperature, both Doenecke Equation and Layer by Layer equations underestimates the experimental data. However, the prediction results of both equation show good agreement with each other. Analysis of heat flux data reveals that the Doenecke Equation is more accurate than the Layer by Layer equation. The comparison of heat flux results of both equations with respect to experimental data is shown in Table 7 and Table 8.

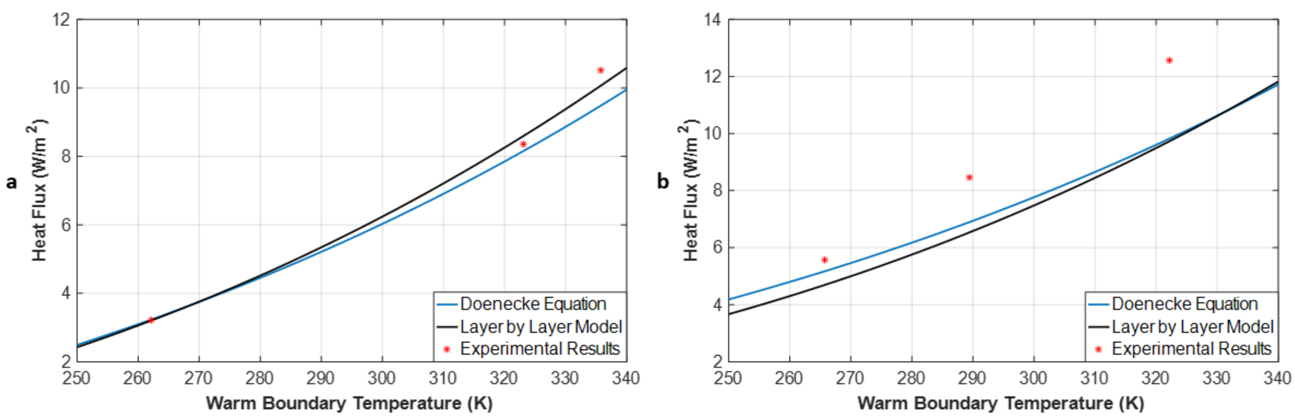

Fig. 4: Experimental and Numerical Results for 22 layer MLI Blanket at 198 K (a) and 146 K (b) Cold Boundary Temperature

Table 7: Heat Flux Results of Investigated Equations for 8 Layer MLI Blanket at 198 K

Warm Boundary Temperature (K)	Layer by Layer Equation Heat Flux (W/m^2)	Doenecke Equation Heat Flux (W/m^2)	Experimental Heat Flux (W/m2)
262.1	3.02	3.22	3.21
323.1	8.42	8.15	8.35
335.8	9.91	9.50	10.51

Table 8: Heat Flux Results of Investigated Equations for 22 Layer MLI Blanket at 146 K

Warm Boundary Temperature (K)	Layer by Layer Equation Heat Flux (W/m^2)	Doenecke Equation Heat Flux (W/m^2)	Experimental Heat Flux (W/m2)
256.4	4.71	4.55	5.57
289.4	6.50	6.87	8.46
322.2	9.71	9.81	12.57

5. Conclusion

For MLI blankets, heat flux estimation accuracy of two different equations were evaluated with respect to an in-house experimental data. In order to utilize these equations, required parameters of MLI blanket samples were obtained. For both equations, MATLAB codes were generated. For 8 layer MLI blanket sample, the Layer by Layer MLI Calculation Using a Separated Mode Equation and Doenecke equation showed average prediction accuracies of 13.2% and 7.3% with respect to the experimental data. For 22 layer MLI blanket sample, the average prediction accuracies are 13.2% and 11.8% for Layer by Layer MLI Calculation Using a Separated Mode Equation and Doenecke equation respectively. Comparing two equations, it was concluded that even though the Doenecke equation heat flux predictions were slightly better, both equations can predict the heat flux through MLI blankets with acceptable accuracies at 146 K and 198 K cold boundary temperatures.

References

[1] D. Gilmore, Spacecraft Thermal Control Handbook, Volume I: Fundamental Technologies. Washington, DC: American Institute of Aeronautics and Astronautics, Inc., 2002. doi: 10.2514/4.989117.

[2] C. L. Tien and G. R. Cunnington, “Cryogenic Insulation Heat Transfer,” in Advances in Heat Transfer, vol. 9, T. F. Irvine and J. P. Hartnett, Eds. Elsevier, 1973, pp. 349–417. doi: 10.1016/S0065-2717(08)70065-0.

[3] G. Cunnington and C. Tien, “A study of heat-transfer processes in multilayer insulations,” in 4th Thermophysics Conference, American Institute of Aeronautics and Astronautics, 1969. doi: 10.2514/6.1969-607.

[4] C. W. Keller, G. R. Cunnington, and A. P. Glassford, “Thermal performance of multilayer insulations,” NASA-CR-134477, Apr. 1974. Accessed: Apr. 03, 2022. [Online]. Available: https://ntrs.nasa.gov/citations/19740014451

[5] A. Hedayat, L. J. Hastings, and T. Brown, “Analytical Models for Variable Density Multilayer Insulation Used in Cryogenic Storage,” presented at the Cryogenic Engineering Conference and International Cryogenic Materials Conference, Madison, WI, Jan. 2001. Accessed: Apr. 03, 2022. [Online]. Available: https://ntrs.nasa.gov/citations/20010021346

[6] G. E. McIntosh, “Layer by Layer MLI Calculation Using a Separated Mode Equation,” in Advances in Cryogenic Engineering, P. Kittel, Ed. Boston, MA: Springer US, 1994, pp. 1683–1690. doi: 10.1007/978-1-4615-2522-6_206.

[7] J. Doenecke, “Survey and Evaluation of Multilayer Insulation Heat Transfer Measurements,” SAE International, Warrendale, PA, SAE Technical Paper 932117, Jul. 1993. doi: 10.4271/932117.

[8] H. Yamaguchi, M. T. Ho, Y. Matsuda, T. Niimi, and I. Graur, “Conductive heat transfer in a gas confined between two concentric spheres: From free-molecular to continuum flow regime,” International Journal of Heat and Mass Transfer, vol. 108, pp. 1527–1534, May 2017, doi: 10.1016/j.ijheatmasstransfer.2016.12.100.

[9] T. M. Flynn, Cryogenic engineering: Second edition, revised and expanded. 2004, p. 914. doi: 10.1201/9780203026991.

[10] R. J. Corruccini, “Gaseous heat conduction at low pressures and temperatures,” Vacuum, vol. 7–8, pp. 19–29, Apr. 1959, doi: 10.1016/0042-207X(59)90766-3.

[11] T. Er, “Evaluation of Multilayer Insulation Performance Equations Available in the Literature,” M.S. thesis, Dept Mech. Eng., Hacettepe Univ., Ankara

[12] C. W. Keller, “Thermal performance of multilayer insulations Final report,” LMSC-A974469, Apr. 1971. Accessed: Jul. 10, 2021. [Online]. Available: https://ntrs.nasa.gov/citations/19710014823

[13] L. Gu, “Generalized Equation for Thermal Conductivity of MLI at Temperatures From 20K to 300K,” in IMECE2003, Heat Transfer, Volume 2, Nov. 2003, pp. 467–473. doi: 10.1115/IMECE2003-41830.