COB-2021-1844

TRANSIENT THERMAL ANALYSIS OF A MULTILAYER INSULATED SYSTEM WITH DIFFERENT OUTGASSING RATES AND THERMAL CONDUCTIVITY.

Guilherme N. Lacerda
Marcos F. Curi
Centro Federal de Educação Tecnológica Celso Suckow da Fonseca, Department of Mechanical Engineering, Rio de Janeiro, Rodovia Mário Covas, lote J2, quadra J, Rio de Janeiro, 23812-101,Brazil
gnegreiroslacerda@yahoo.com.br, marcos.curi@cefet-rj.br

Abstract. *Thermal control in space has some relevant subjects. The system most used for thermal insulation in space is the Multilayer Insulation (MLI) blanket. Consisting on an amount of highly reflective material - layers- and low thermal conductivity - spacer. The literature has been studied predominantly by experimental tests over the years, but with the computational evolution, numerical analysis becomes possible. This work aims to analyze numerically the impact of the outgassing rate of the material applied to a layer and the type of spacer used. Using libraries of Python was possible to solve the ODE's and the iterative system formed by the problem. The condition was the spacecraft in the shadow, so the temperatures were 4K for the space environment and 300K for the spacecraft surface. The results of the temperature field in simulations show that using a material with low outgassing impact in a low temperature in the last layer. The spacer commonly used is glass fiber, which has the calculation of its thermal conductivity large tested, the polymer pin as a spacer is an alternative way presented by literature. The comparison between MLIs using glass fiber, polymer films, and polymer pins as a spacer was made. The polymer pin heat transfer was simplified, and its thermal conductivity does not vary in time.*

Keywords: *Multilayer Insulation, Aerospace Engineering, Outgassing, Numerical Heat Transfer*

1. INTRODUCTION

An essential subject about thermal control in mechanical engineering is the variety of techniques for thermal insulation and its wide research field among the literature and actual applications. Equipment such as electronic devices depends on temperature control for applications in severe environmental conditions, for example, space-based equipment, which is the scenario under analysis. In that sense, space thermal control often uses the Multilayer Insulation (MLI) to isolate the heat flux in spacecraft to the outer environment, as seen in Gilmore (2001). The design of MLI depends on specific parameters and variables that have a direct impact on its performance.

Knowing how to choose an ideal combination of them is extremely important for a correct functional system, leading to an accurate prediction of the MLI performance. The parameters such as thermal conductivity, outgassing rate, and spacers are on focus in this paper. The literature is predominantly based on experimental studies to calculate the performance of MLI. Due to its complexity, theoretical analysis and computational simulation of MLI performance, which provides high accuracy results,became an attractive research field to reduce the costs of the experimental equipment.

Nowadays each aerospace-engineering mission where MLI blanket is requested have a unique design, that increases the laboratory tests using a specific design for the MLI, becoming an expansive and long-term project for reach the ideal MLI (Devi and Rao (2018) and Miyakita *et al.* (2019)). Thus, an accurate numerical method is able to test multiples variations, hard to reproduce in laboratory, in that sense saving costs and time of the project.

The theoretical model of the heat transfer in MLI was presented in Zhitomirskij *et al.* (1979). Recently Li and Cheng (2006) showed an application of this method in other space conditions such as in the shadow. Lacerda and Curi (2020), studied the impact of different layers density, emissivity, the distance between screens and the perforation coefficient in stationary and transient approaches. Alternatives for different spacers also increases the possibilities for different configurations to build a MLI blanket.

This paper aims to perform a numerical simulation and to determine the temperature field and heat flux across the layers contributing to reliable theoretical data for different outgassing rates and two different spacers between the MLI layers: glass fiber, highly studied in Bapat *et al.* (1990) and polymer pins, an alternative presented in Miyakita *et al.* (2019). Today with 3D print is easier to make particular parts in polymers, turning possible produce your own spacer.

The mathematical approach based on transient governing equations of fluid mechanics and radiation-conduction heat

transfer leads to a coupled non-linear ODE system, solved by two subroutines from Python library. The temperature boundary conditions used for the numerical analysis were 4K and 300K for the outer space and the insulated surface, respectively. Therefore, the data given by the solutions are strict to the conditions that were set. Then, an analysis from the simulations is made for the best combination to build a MLI blanket.

2. SOLUTION METHODOLOGY

Equation (1) is a discretized transient one-dimensional ODE and is the global equation of the heat transfer acting inside the MLI blanket in transient case. This governing equation is based on energy balance, Lacerda and Curi (2020), taken each layer as a node.

$$\xi_i' \varepsilon_i (F_{1,i} + F_{2,i} - 2\sigma T_i^4) + \frac{k_i}{\delta_i}(T_{i-1} - T_i) - \frac{k_{i+1}}{\delta_{i+1}}(T_i - T_{i+1}) = \rho_i c_i t_{c,i} \frac{dT_i}{dt} \tag{1}$$

Where i is the index of the layer, c is heat capacity, ρ is density of reflective screen, t_c is the thickness of the screen, δ is the distance between the screens, ξ is the perforation coefficient, ξ' is $(1 - \xi)$, F_1 and F_2 the incident radiant flux in a node, ε is the emissivity of the material and ε' is $(1 - \varepsilon)$.

Figure 1 shows a diagram that resumes all the implemented code. With the initial conditions set, the program starts calculating the thermal conductivity, then the flux of incident radiation is possible to be calculated. By using the Pyhton libraries Numpy and Scipy (Bressert (2012)), that uses Levenberg-Marquardt method for root finding, it was possible to calculate the layer temperature field. For each layer, the code verifies if the new temperature calculated is different from the previous temperature. If it has changed, the process restarts and continues until the temperature achieves a convergence range with a difference lower than 0.001K.
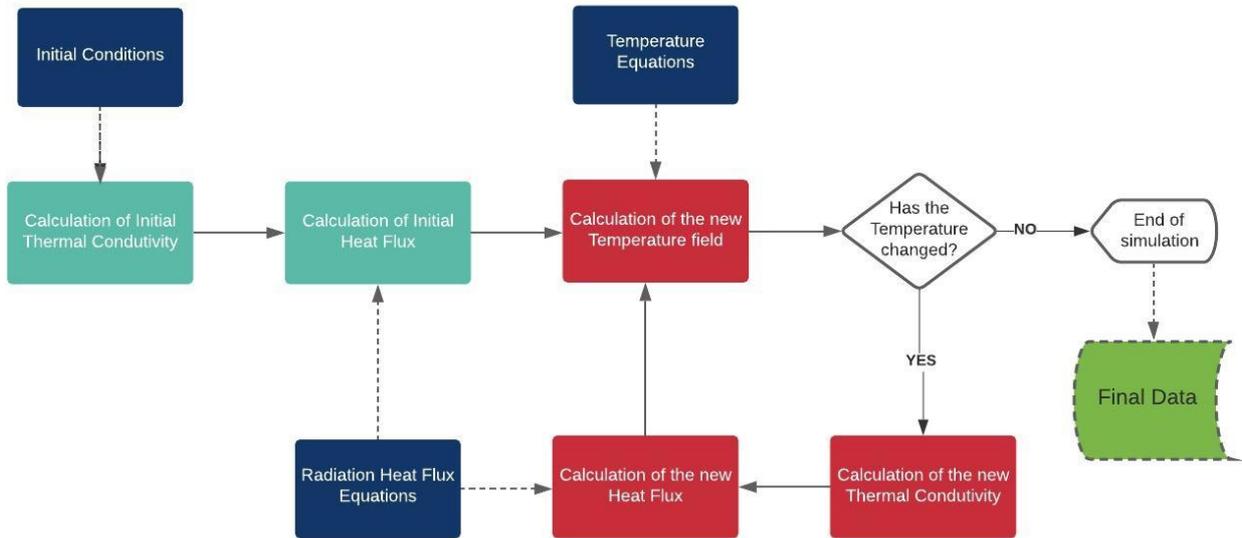

Figure 1. Schematic diagram of the control strategy.

2.1 Thermal conductivity

The thermal conductivity depends on the spacer chosen. When glass fiber is used in the simulation, its thermal conductivity varies in each step. The other combinations for the spacer in the MLI blanket were a flat film with low conductivity and polymer pins, decreasing the contact area.

Glasse fiber is an option widely studied in the literature, Bapat *et al.* (1990) has presented a calculation for thermal conductivity. Figure 2 shows how organized the fiberglass is to materialize the spacer in the MLI blanket. This spacer considered the conductivity due to the gases between the spaces between the glass fibers, Li and Cheng (2006) has presented the empiric calculation for this contribution to the global thermal conductivity.

Equation 2 was obtained by a semi-empirical method in Zhitomirskij *et al.* (1979).

$$k_{sp} = An^K k_g(T) \tag{2}$$

Where A and K are empirical coefficients, A depends on n, and n is the layer density. Being k_g given by Eq. 3.

$$k_g(T) = 0.22 + 0.26T/10^2 \tag{3}$$

The temperature in Eq. 2 is the arithmetic average between the temperatures of screens around the spacer. This formula is presented in Mazurin *et al.* (1983).

Equation 4 is the contact thermal conductivity between the spacer and the screen.

$$H = 2\xi' r k_m \tag{4}$$

Where r is the contact radius between spacer and screen, Eq. 5. The thermal conductivity equivalent of the screen and the spacer, k_m, given by Eq. 6.

$$r = (0.75\pi(K_{sc} + K_{sp})Pt_p/N_T^2)^{1/3} \tag{5}$$

$$k_m = 2k_{sc}k_{sp}/(k_{sc} + k_{sp}) \tag{6}$$

where k_{sp} and k_{sc} are the thermal conductivity of the spacer and the screen, respectively.

The solid equivalent thermal conductivity between the screens, Eq. 7.

$$k_{eq,s} = \frac{\delta}{1/H + \delta/k_{sp}} \tag{7}$$

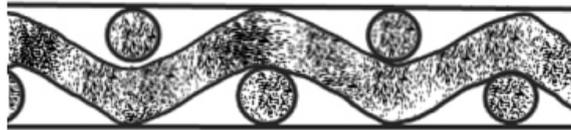The total thermal conductivity is the sommatory of Eq. 7 and Eq. 8.

Figure 2. Schematic diagram of the spacer made of glass fiber.

The flat film is a simple combination of layers with reflective material and low conductivity stacked in sequence. On the other hand, the polymer pin is a more complex spacer for visualizing.

Figure 3 shows a model of MLI with the polymer pins as a spacer. The heat transfer in this spacer is not simple, Figure 4 shows a diagram of how the heat works in the polymer pins. This work considered only the conduction heat transfer and without radiation between the pins. Miyakita *et al.* (2019) has presented experiments using this spacer in MLI.
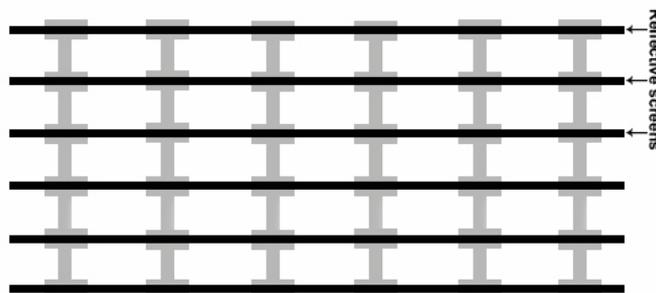

Figure 3. MLI with spacer of polymer pin.

An MLI with either glass fiber or polymer pin spacers has gases in your inside, as is possible to see in Fig. 2 and Fig. 4. This study used an intrinsic parameter of material called Outgassing rate to calculate the impact of these gases on thermal conductivity.

2.2 Outgassing

For using perforated screen, the gas thermal conductivity used is Eq. 8, given by Chen *et al.* (1994):

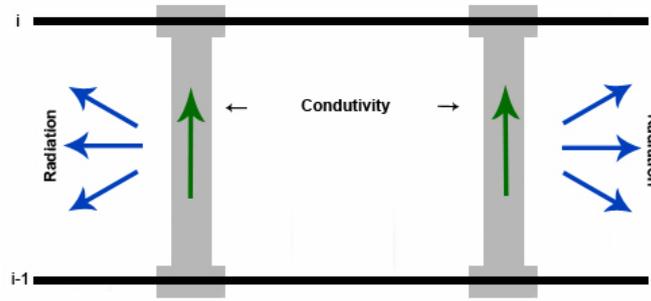$$k_{eq,g} = a\nu R N^2 \frac{\xi'}{\xi}\delta_t \tag{8}$$

Figure 4. The heat transfer in the spacer of polymer pin.

where a is accommodation coefficient, ν is the outgassing rate in one side of the screen, R is the gas constant, δ_t is total thickness of the MLI and N is the number of layers.

Glassford and Liu (1980) has presented a study where the value of the outgassing of materials in ambient temperature were measured. The outgassing rate of the material, defined as the mass of gas per area going out in time, is given by:

$$\nu = \nu_0 \frac{T_0}{T} e^{-(E_d/2R)(1/T - 1/T_0)} \tag{9}$$

where ν_0 is the outgassing rate at the temperature T_0, E_d is the activation energy for diffusion.

2.3 The incident radiant flows

Figure 5 is a schema that shows the flux of radiation between layers. In a perforated MLI this radiation flux pass through them, given the Eq. 10 and Eq. 11. This equations that expose the sum of radiation of its own temperature with the radiation given by the layers around that go throw the little perforations.
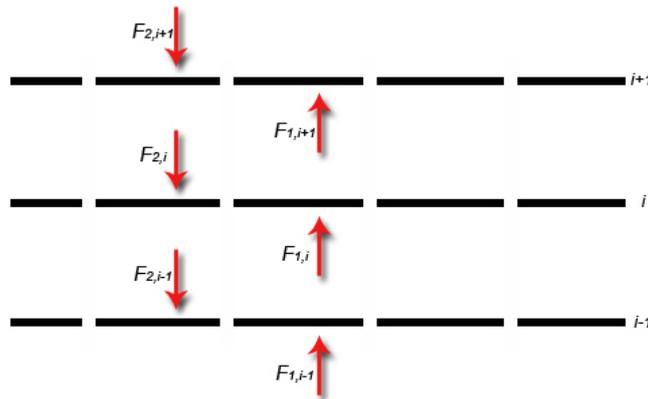

Figure 5. Diagram of the incident radiant flux.

$$F_{1,i} = \xi'_{i-1}\varepsilon_{i-1}\sigma T_{i-1}^4 + \xi_{i-1}F_{1,i-1} + \xi'_{i-1}\varepsilon'_{i-1}F_{2,i-1} \tag{10}$$

$$F_{2,i-1} = \xi'_i\varepsilon_i\sigma T_i^4 + \xi_i F_{2,i} + \xi'_i\varepsilon_i F_{1,i} \tag{11}$$

3. RESULTS AND DISCUSSIONS

Figure 6 shows the different behavior in each simulation for different Outgassing rates of the material. It is possible to see that the outgassing rates significantly change the response in temperatures in layers when the temperatures are stable. Table 1 shows the temperature of the last layer of MLI blanket simulated in the stationary case. Then, using a material with outgassing rates lower give a decrease in temperatures.
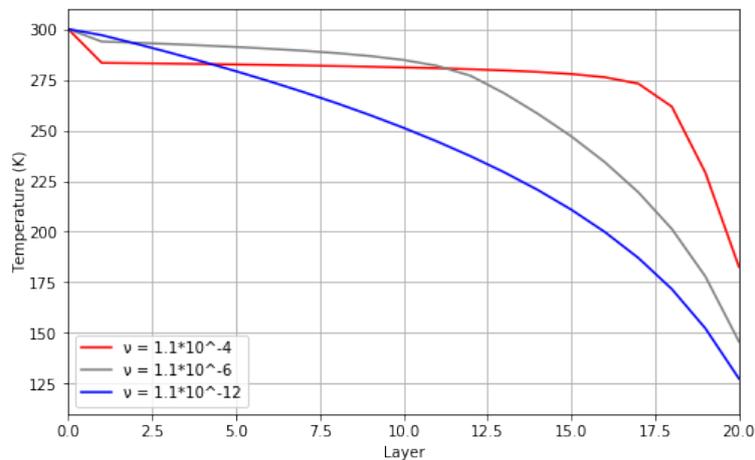
Figure 6. Varying outgassing in stationary case.

Table 1. The temperature of last layer changing the outgassing, in steady state.

Outgassing, (Kg/m²)/s	Temperature, K
$1,1 \cdot 10^{-4}$	182.6878
$1,1 \cdot 10^{-6}$	145.8237
$1,1 \cdot 10^{-12}$	127.5132

Figure 7 shows the behavior in each simulation. It is possible to see that the outgassing changes the time in the last layer, and interrupts the temperature variation. Table 3 shows the last layer temperature of the MLI blanket simulated in the transient case and the time of convergence. So with lower outgassing rate reach a lower temperature and taking more time.
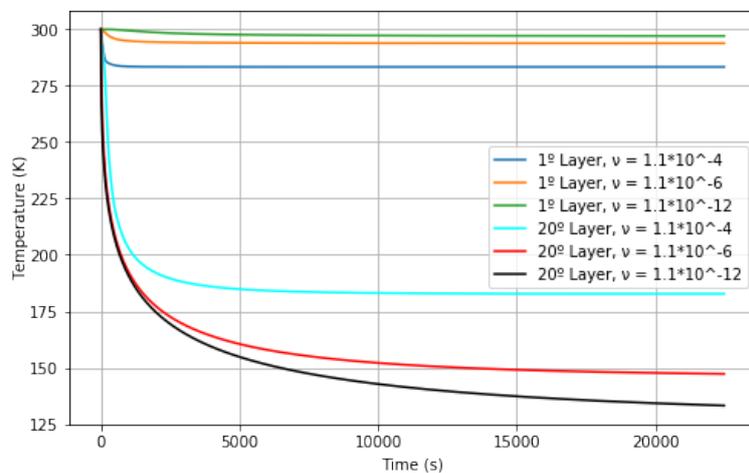

Figure 7. Varying outgassing in transient case.

Table 2. The temperature of last layer changing the outgassing and time of convergence.

Outgassing, (Kg/m²)/s	Time, s	Temperature, K
$1,1 \cdot 10^{-4}$	15003	182.8012
$1,1 \cdot 10^{-6}$	45220	146.0356
$1,1 \cdot 10^{-12}$	84484	127.8323

Figure 8 and Figure 9 are the respectively stationary and transient cases varying the spacer used in simulations. With polymer pins, the contact area is smaller than using a polymer film. Table 1 shows the temperature of the last layer of MLI blanket simulated in the stationary case. In Fig. 9 the blue line is almost superimposed by the green line, as is possible to see in the first layer the difference is little than in the last layer varying only the spacers.

Table 3. The temperature of last layer changing the spacer and the time of convergence.

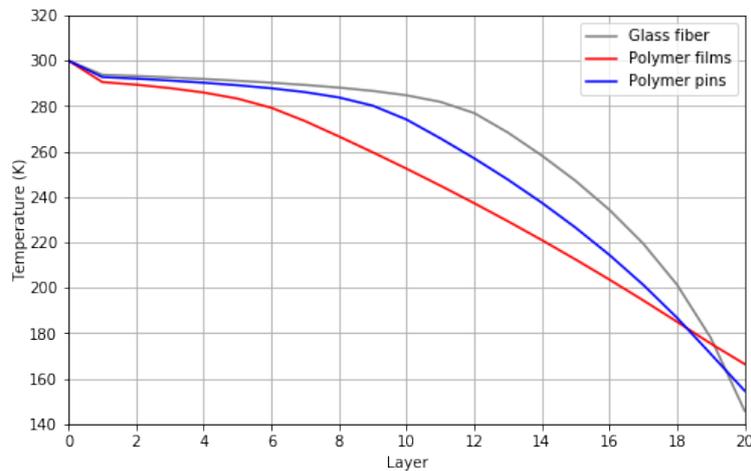| Spacer	Time, s	Temperature, K
Glass fiber	45220	146.0356
Polymer films	26518	166.5161
Polymer pins	34856	154.8097

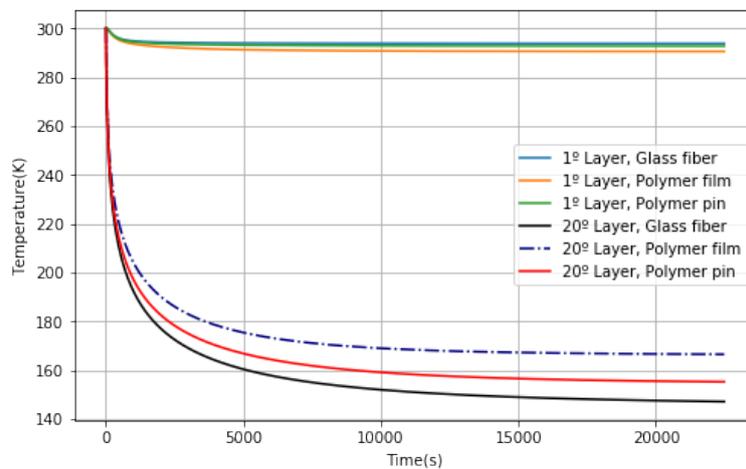Figure 8. Comparison between spacers in stationary case.

Figure 9. Comparison between spacers in transient case.

4. CONCLUSIONS

The results exposed in this work show the importance of numerical simulation in heat transfer of MLI blanket, reducing time and providing a direction about changes in MLI design. Although, experiments in an appropriate laboratory are required. Different outgassing rates result in changing the material used in MLI. Thus, picking a material that satisfies the others requisites of an MLI blanket with a lower outgassing rate forms a better composition. In these simulations, the fiberglass was calculated with more accuracy, given its thermal conductivity by empirical formulation, more studies around polymer pin as a spacer in MLI blanket are necessary for better conclusions.

5. REFERENCES

Bapat, S.L., Narayankhedkar, K.G. and Lukose, T.P., 1990. "Performance prediction of multilayer insulation". *Cryogenics*, Vol. 30, pp. 700–710.

Bressert, E., 2012. *SciPy and NumPy*. O'Reilly Media, 1005 Gravenstein Highway North, Sebastopol, 1st edition.

Chen, G., Sun, T., Zheng, J., Huang, Z. and YU, J., 1994. "Performance of multilayer insulation with slotted shield". *Cryogenics*, Vol. 34, pp. 381–384.

Devi, S.K. and Rao, Y.V.H., 2018. "The optimization of layer densities for multilayered insulation systems by using ansys". *Trans Stellar*, Vol. 8, No. 4, pp. 1087–1098.

Gilmore, D.G., 2001. *Spacecraft Thermal Control Handbook*. The Aerospace Corporation, California, 2nd edition.

Glassford, A.P.M. and Liu, C.K., 1980. "Outgassing rate of multilayer insulation materials at ambient temperature". *Journal of Vacuum Science and Technology*, Vol. 17, No. 3, pp. 696–704. doi:10.1116/1.570544.

Lacerda, G.N. and Curi, M.F., 2020. "Heat transfer investigation for a multilayer insulation system via radiative-conductive approach under low temperature conditions in space". *RETERM ISSN: 1676-1790*, Vol. 19, pp. 70–76.

Li, P. and Cheng, H., 2006. "Thermal analysis and performance study for multilayer perforated insulation material used in space". *Applied Thermal Engineering*, Vol. 26, pp. 2020–2026.

Mazurin, O.V., Streltsina, M.V. and Shvaiko, T.P., 1983. *Handbook of Glass Data*. Elsevier Science Publishing Company, New York, volume 15, part a edition.

Miyakita, T., Kitamoto, K., Kinefuchi, K., Sugita, H., Saitoh, M. and Hirai, T., 2019. "Development of a new mli for orbital cryogenic propulsion systems -thermal performance under one atmosphere to a vacuum". *IOP Conf. Series: Materials Science and Engineering*, Vol. 502, pp. 1–5.

Zhitomirskij, I.S., Kislov, A.M. and Romanenko, V.G., 1979. "A theoretical model of the heat transfer processes in multilayer insulation". *Cryogenics*, Vol. 19, pp. 265–268.

6. RESPONSIBILITY NOTICE

The authors are solely responsible for the printed material included in this paper.