Study of thermal performance of the Multilayer Insulation Technique in cryostats for rare physics search experiments

Damini Singh[1,2*]
[1]*Department of Physics, Institute of Science, Banaras Hindu University, Varanasi, Uttar Pradesh, 221005, INDIA. and*
[2]*Department of Physics, Gujarat Arts and Science College, Ellisbridge, Ahmedabad, Gujarat, 380006, INDIA.*

Introduction

The causes and effects of extremely low temperatures on different physical systems are investigated using the techniques of cryogenics. A number of thermal insulation methods have been developed to stop cryogenic liquids from boiling off due to thermal effects. These things are now examined in numerous other fields. The efficient functioning any thermal insulation depends on the amount of heat transmission as a result of temperature change by the following processes: (a) solid conduction; (b) convection; and (c) thermal radiation. In the case of the most demanding applications, engineers generally take a special Multilayer Insulation (MLI) approach to reduce radiative heat transfer. In the cryogenics and space industries, MLI is a vital and essential insulating technique that has been utilized successfully. It consists of radiation shields, often called reflecting layers since highly reflective materials are used to polish them on both the sides. The purpose of a coating is to reflect the bulk of thermal radiation. In order to reduce the solid conduction heat transfer from one reflecting layer to the next due to their adjacent positioning, a low thermal conductivity material known as a spacer is positioned between two reflecting layers. The radiation shields and spacers are layered between the hot and cold wall boundaries of the cryostat (a container used for the mechanical housing of a detector and cryogenic liquid). The MLI technique is fundamentally relies on the concept of multiple reflections of incident radiation [1, 2].

Theoretical and empirical models

The modes of heat transmission through the MLI blanket must be taken into account while investigating the thermal performance of the MLI technique. For the thermal performance of the MLI technique, the most widely used empirical and theoretical models are taken, which are Lockheed Martin Flat Plate equation, Modified Lockheed equation, and McIntosh Layer-by-layer approach. As MLI systems are known to be composed of multiple layers of radiation shields interspersed with spacers, these models have the influence of boundary temperatures (T_1 and T_2), the number of layers (N), the layer density ($\bar{N}$), and the thickness of the MLI blanket. Perforated DAM with Dacron, Unperforated DAM with Silk-Net, and Perforated DAM with Glass-Tissue are the three proposed material combinations for our analysis [1, 2].

Results and discussion

After the selection of all the constant values ([1]) required to conduct the performance modeling of the MLI approach, the consequence of increased layer density and number of layers on the heat load are investigated, and the most effective layer density for the three material combinations is determined by using the above-mentioned models [1].

We evaluated the effect of increasing the number of layers for the three suggested materials, which demonstrates an expected decrement in heat load as predicted by the MLI approach. As a general strategy to reduce the radiation heat load, the installation of a large number of radiation shields could be

*Electronic address: daminisinghphy27@gmail.com; Electronic address: damini0physics@gmail.com

used. However, as the layer density increases, so does the heat load due to an increase in solid conduction between the radiation shields via the spacers. As a result, layer density optimization is required. In this sequence, the most optimal layer density is determined by monitoring how solid conduction and radiation heat loads respond to layer density. This pattern of behaviour demonstrates a point of equilibrium between the solid conduction and radiation heat loads, which is equivalent to the appropriate value of layer density [1].

Following the selection of all the constant values ([2]) necessary to optimize the MLI performance modeling, the impact of the physical characteristics associated with the MLI technique on the heat load is studied by using both theoretical and empirical models. The emissivity of the radiation shields, the residual gas pressure between the two wall boundaries of the cryostat, the perforation and unperforation of the radiation shields, the thickness of the spacer material towards the cold wall of the cryostat, and the configuration of the radiation shields are the effective physical parameters [2].

In the evaluation of the impact of the emissivity of the radiation shields on the heat load, it was found that a correlation between the emissivity and T_1 greatly increases the contribution of the radiation heat load in the overall heat load. In analysing how the residual gas pressure between the two wall boundaries of the cryostat affects the heat load, it is discovered that for all three of the selected material combinations for the MLI blanket, the gas conduction heat load grows as the vacuum level diminishes [2].

Different perforation styles are taken into consideration in the investigation of the significance of perforation and unperforation, and we have identified the ideal perforation style to utilize in the MLI technique for ground-based rare physics investigations. The perforated DAM with Silk-net is an excellent choice if employed as a radiation shield and spacer material combination for the low-temperature region since it has the lowest heat load value with Perforation Style A [2].

The thickness of the spacer material (position of the first radiation shield) from the cold wall boundary towards the hot wall boundary of the cryostat has been investigated, and it is shown that the conduction heat load decreases rapidly as this thickness increases. It indicates that a better performance could be achieved by positioning the first radiation shield as far away from the cold wall boundary as is physically possible. It implies that the thickness of the spacer should be larger towards the cold wall boundary of the cryostat [2].

The strategic positioning of the radiation shields has an impact on the thermal performance of the MLI technique. The solid conduction part of the total heat load is selected to determine the effect of radiation shield's arrangements on the heat load. For this analysis, we have three alternative configurations of the radiation shields: uniform spacing, increasing spacing, and decreasing spacing towards the hot wall boundary of the cryostat. The decreasing spacing from the cold wall boundary towards the hot wall boundary of the cryostat has been demonstrated as the best configuration because of having the lowest amount of heat load [2].

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References

[1] D. Singh et al., Journal of Instrumentation **15**, P07032 (2020).

[2] D. Singh et al., Heat Mass Transfer **59**, 1365–1378 (2023).