Effects of emissivity on multilayer insulation technique and the role of multilayer insulation technique in the cryostats

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Introduction

Most of the time, a cryostat's heat load should be kept at the lowest possible level because a significant amount of it is typically undesirable. This entails financial costs and obstructs cryogenic application progress for those experiments which are potentially involved in achieving the background-free environment in the searches of rare physics events of dark matter, neutrinoless double β-decay, sterile neutrinos, etc. It is possible to achieve outstanding thermal insulation efficiency by using the multilayer insulation (MLI) approach which consists of radiation shields and spacers materials [1]. Since it has a low thermal conductivity, broad implications, and immediate impact on heat transport, this method is widely used as a passive thermal protection system in cryogenic operations [2].

Heat load exchange model

There are three models, which are the most versatile for determining the MLI technique's outstanding outcome. The first one is Modified Lockheed equation, second is Lockheed Martin Flat Plate equation and the third analytical Layer−by−Layer approach is the physics−based expression developed by McIntosh for the theoretical calculation of the heat load in MLI system. Modified Lockheed equation, which took into account all three types of heat exchange-radiation, solid conduction, and gaseous conduction is used here to evaluate the effectiveness of MLI technology with the help of all empirical constants (C_r, C_s and C_g) and is expressed as

$$q^{\text{total}} = \frac{1}{l} C_r \, \varepsilon \, (T_1^{4.67} - T_2^{4.67}) + \frac{1}{2\,(l+1)} C_s \, \bar{l}^{2.63} (T_1^2 - T_2^2) + \frac{1}{l} C_g \, P \, (T_1^{0.52} - T_2^{0.52}), \quad (1)$$

where T_1 and T_2 are the temperatures (in K & $T_1 > T_2$) of the hot and cold wall boundaries, respectively, l is the number of layers and $\bar{l}$ is the layer density (l/cm) [3].

Results and discussion

It is necessary to optimise the effective parameters for the MLI approach to perform reliably. The pressure (P) developed between the hot and cold wall boundaries, emissivity (ε) of radiation shields, perforation in radiation shields, and radiation shield placement are only a few factors that may be extremely important to the effectiveness of MLI approach. Here we have used Modified Lockheed Eq. 1 for the investigation of the effect of ε of radiation shields on the total heat load. Emissivity influences the overall heat load (primarily the radiation heat load). The intervening medium in this investigation is made up of three suitable spacer and radiation shield materials: perforated Double Aluminized Mylar (DAM) with Dacron, perforated DAM with Glass−tissue, and unperforated DAM with Silk−net.

Emissivity is directly proportional to the radiation heat load which is produced in the

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MLI technique as clear from Eq. 1. The effect of ε on the total heat load can be understood from Fig. 1. To illustrate the performance in terms of emissivity, the values of l = 40, the value of $\bar{l} = 20\ l/cm$ and P is selected as 10^{-4} Torr. Three experimentally feasible values of $\varepsilon \equiv (0.01,\ 0.1,\ 0.5)$ are chosen for the three selected combination of materials.

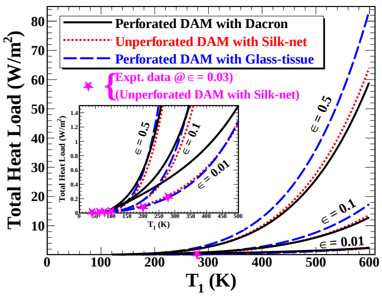

FIG. 1: The effect of ε of radiation shields on the total heat load is shown while keeping the same T_2 = 77.4 K.

Fig. 1 shows that the total heat load increases with ε and T_1. As ε increases, maximum absorption of the incident radiation takes place by the first radiation shield. This leads to the increment in T_1 (due to backward re−emission of thermal radiation) and the temperature of first radiation shield. However, due to multiple reflections of radiation by the successive radiation shields, a very small amount of the heat load reaches to the cold wall boundary [2]. It follows that the value of T_2 will nearly remain constant. Therefore the difference $(T_1 - T_2)$ increases, which leads to the increment of total heat load as ε of the radiation shields increases.

A variation in the total heat load with ε is examined at $T_1 \equiv$ (87.3 K, 165 K, 300 K) temperature, while keeping the T_2 = 77.4 K and the results are displayed in the Fig. 2, respectively. It shows the effectiveness of the proposed material combinations over a wide range of ε.

In particular, reduction in the heat load is comparatively furthermore significant due to layering near inner wall of the cryostat [1]. As an example, in the case of LEGEND-1T

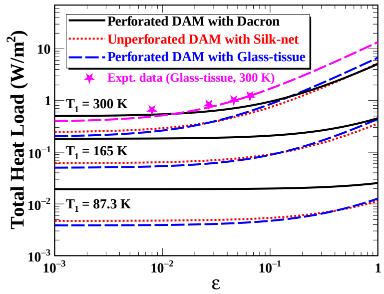

FIG. 2: Variation in the total heat load with ε at $T_1 \equiv$ (87.3 K, 165 K, 300 K) and T_2 = 77.4 K.

with spherical cryostat, the heat load reduces by 40% (57%) near outer wall (inner wall), and 41% (56%) near outer wall (inner wall) with cylindrical cryostat as seen in the Fig. 3. Therefore a cylindrical cryostat even with a single layer near inner wall would be a good choice for large-scale experiments [2].

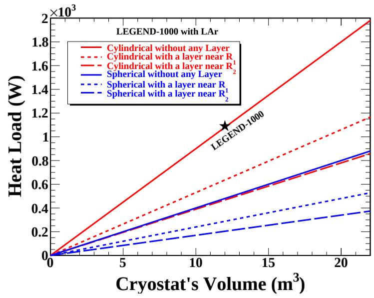

FIG. 3: Impact of a single layer MLI technique in reducing the heat load as a function of cryostat's volume, in LEGEND-1T with LAr

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