Performance characterization of perforated multilayer insulation blankets

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Perforated multilayer insulation (MLI) blanket systems are targeted for large-scale cryogenic facilities. Space applications and particle accelerators are two fields concerned with thermal shielding of cryogenic devices. Because radiation heat transfer varies with T^4, heat transfer in the range of 300 K to 77 K is dominant even for devices operating at temperatures as low as 2 K. Systems operating under conditions of degraded vacuum levels are also a key consideration because of heat transfer by residual gas conduction. The results of an experimental study of a perforated MLI blanket system using a steady-state liquid nitrogen evaporation method are presented.

INTRODUCTION

Thermal performance of multilayer insulation (MLI) systems in large-scale or industrial applications is the subject of this paper. Thermal losses due to radiation at the temperature range 300-77 K are more than 2 orders of magnitude greater than at the range 77-5 K. Characterization of MLI performance at this upper temperature range is therefore of prime importance. For aerospace applications cryogens are often used in thermal shielding of spacecraft instruments. In the case of the Large Hadron Collider (LHC) under construction at CERN, the cryostat includes a thermal shield actively cooled at 50-75 K. The total equivalent refrigeration power from ambient to 1.8 K has been estimated to be around 500 MW, including more than 3 MW of installed cryogenic power at 50-75 K [1]. Thermal insulation systems are important to reduce the energy bill and to provide reliable control of the cryogenic plants. Measurements of MLI performance are needed to provide information to budget the LHC cooling power. Heat transfer by conduction in residual gas, due to the vacuum insulation pressure, is an important contribution to the total heat load through the MLI system. Therefore the use of the perforated MLI blanket system, now being used for the LHC cryostats, shows its principle in providing a lower pressure between layers. This system also has applications for space launch vehicles and cryogenic spacecraft that operate in the high vacuum condition of space but are also subjected to atmospheric pressure conditions.

EXPERIMENTAL

The liquid nitrogen boiloff method utilizing a cylindrical cryostat was used for all tests [2]. The configuration includes a cylindrical cold mass with liquid nitrogen guard chambers. Sensors are placed between layers of the insulation to obtain temperature-thickness profiles. The insulation test specimen is wrapped around the cold mass of a vertical cryostat. The temperatures of the cold mass [cold boundary temperature (CBT)], the insulation layers, the outer insulation layer [warm boundary temperature (WBT)], and vacuum chamber are measured as shown in Figure 1a. The end boundary effects of the 167-mm diameter, 910-mm length cold mass are minimized by using an effective length of 575 mm. The k-value is the apparent thermal conductivity for the total insulation system, in milliwatts per meter-kelvin (mW/m-K). A thermal shroud on the vacuum chamber kept the WBT at approximately 293 K while the liquid nitrogen cold mass maintained the CBT at approximately 78 K.

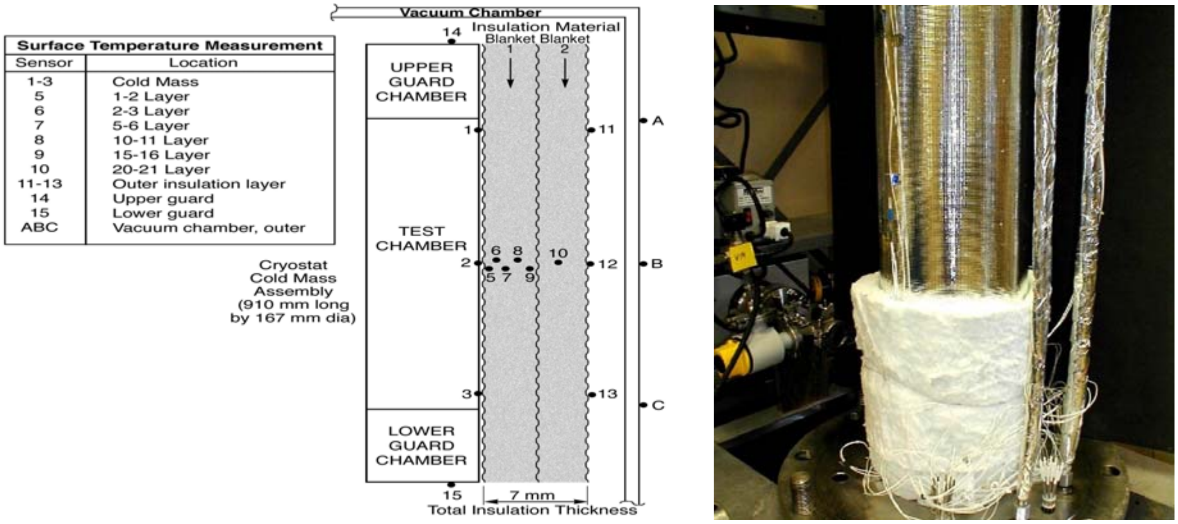

Figure 1. (a) Configuration of MLI blankets and temperature sensors, (b) Final installation showing lower portion of cryostat.

The test specimen was a combination of two perforated MLI blankets manufactured by Jehier (Chemille, France). Each blanket was 15 layers (15 pairs) of perforated reflector layers and spacer layers held together at the edges by nylon tag pins. The outer reflector layer was a 20 μm double-aluminized polyester film reinforced by glass fiber. The inside reflector layers were 6 μm thick polyester films doubly aluminized to 400 Angstroms and perforated with 2-mm holes at a spacing of 56 mm. The spacer layers were 0.02 mm thick polyester tulle (5 g/m^2) with a 2x3 mm^2 mesh.

The blankets were laid out on a table for measurement and trimming to the required size. After the delicate task of installing the temperature sensors within the blanket, the blanket was installed onto the cold mass by the use of spring fasteners to hold and position the blanket. The temperature sensors were platinum resistance type with lead wires approximately 1.5 m in length to minimize conduction heat load. A longitudinal seam with an overlap of approximately 19 mm was created by using additional spring fasteners. The seam was taped down using low outgassing, aluminized plastic tape. All spring fasteners were removed in a sequential fashion. This process was then repeated for the second blanket. The seam was positioned opposite from the seam of the first blanket. The completed test specimen installation including the cold mass closeout materials is shown in Figure 1b. The total thickness of the 30 layers was 7 mm (density of 4.3 layers/mm). Test preparations included vacuum pumping and heating of the MLI blanket for about 1 week. The initial heating was performed at approximately 350 K.

TEST RESULTS AND DISCUSSION

Summary graphs of the heat flux and the apparent thermal conductivity (k-value) as functions of cold vacuum pressure (CVP) are presented in Figure 2. The mean surface area of the cylindrical blanket was used in the calculation of the heat flux. The layer temperature profiles as a function of blanket thickness for the different cold vacuum pressures are presented in Figure 3. The temperatures of the cold boundary surface and the warm boundary surface were measured in several locations to verify stability and uniformity of the layer temperature measurements. The temperature read-outs for this large span of temperatures were typically within +/- 1 K. An analysis of the test measurement system indicates an overall uncertainty of less than 5 percent with temperature, heat of vaporization, and fluid density being the dominant factors. The WBT is a strong function of the CVP as indicated by the curves for the 1 torr and 5 torr cases. The thermal shroud heaters were at maximum operating temperature for these two cases. The result was that the WBT could only be maintained at about 230 K rather than the normal WBT of 293 K. Information on the performance of the perforated MLI blanket in comparison to other MLI systems under similar conditions can be found in the literature [3].

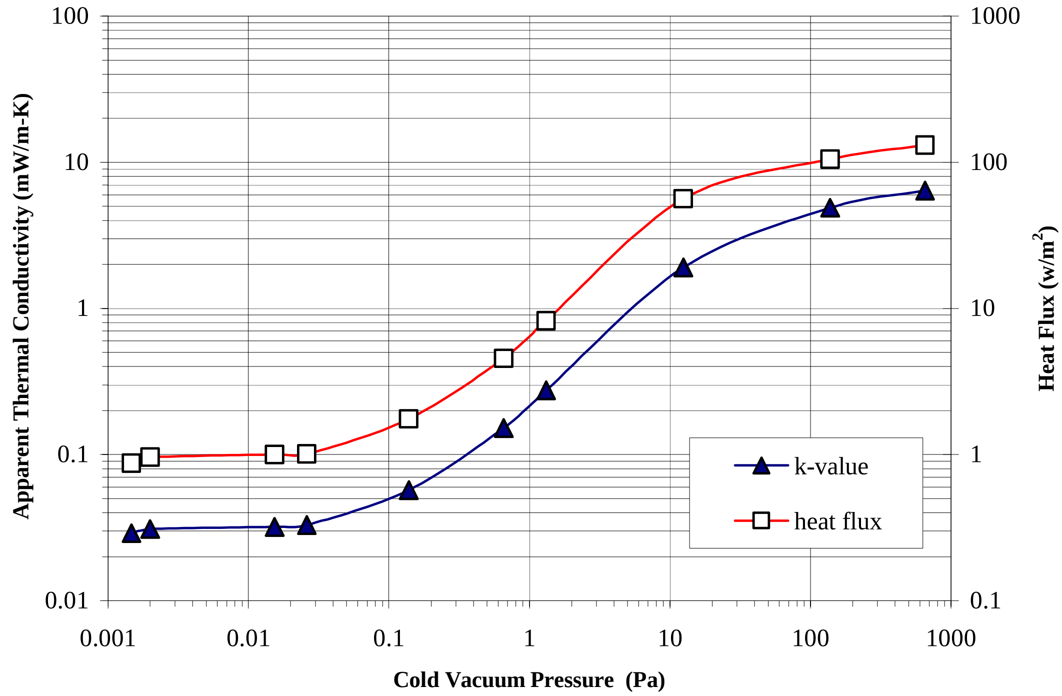

Figure 2. Variations of apparent thermal conductivity (k-value) and heat flux with cold vacuum pressure (CVP).

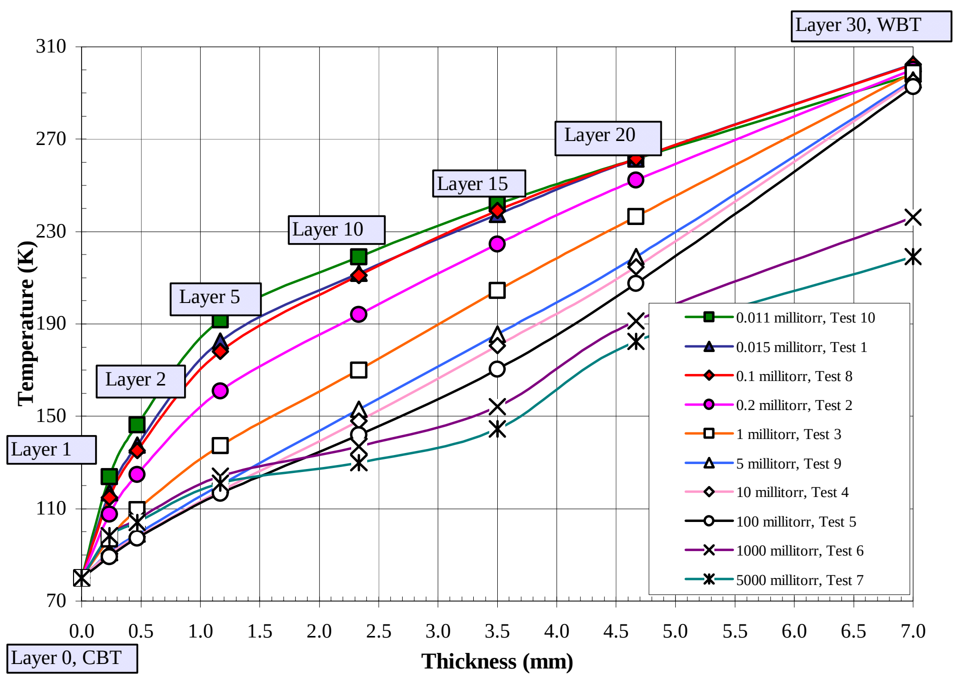

Figure 3. Variation of layer temperatures with blanket thickness for different cold vacuum pressures (1 millitorr = 0.1333 Pa).

ANALYSIS AND APPLICATION

The high vacuum level performance compares well with the best MLI constructions published in the literature. The temperatures for layers 1 and 2 were measured to be 124 K and 146 K, respectively, for the high vacuum case (0.0015 Pa, or 0.011 millitorr). Previous measurements from CERN performed on a 10-m long cryostat thermal model with the same MLI showed similar results [4]. More measurements have been dedicated to MLI performance at CERN using a lower layer density and different packing factors [5-6]. The higher heat flux in our case is attributed to tighter packing and a greater effect of the seams on the smaller surface area. Other tests performed by Keller and by

Shu confirm the current results [7-8]. For a similar MLI under similar conditions to the blanket of this study, the heat flux was measured to be from 0.30 W/m^2 (for 80 layers at 2.82/mm) to 3.6 W/m^2 (for 20 layers at 4.86/mm). For 80 layers at high density or 20 layers at low density the heat flux was about the same at around 1 W/m^2 [7].

The choice of the packing factor and the assembly procedure are important to characterize any MLI system thermal performance. Information comparing the performance of ideal and actual MLI systems has been previously reported. Localized compressive damage, as caused by a typical support structure, was shown to cause an increase in heat transfer of over 60 percent [9]. The system with its durable face sheets makes installation and joining techniques reasonable for other large-scale systems. The perforations of the reflector layers minimize the problematic issue of evacuation of large systems.

The temperature profiles give clear evidence of the detrimental effects of residual gas conduction. At degraded vacuum levels the temperature gradients are nearly constant through the blanket thickness, whereas for high vacuum this gradient profile becomes logarithmic. This characteristic emphasizes the importance of removing the residual gases from inner to outer layers through the perforation holes.

CONCLUSION

The results of this experimental study give the thermal performance of a perforated MLI blanket system of insulation (30 layers, 4.3 layers/mm) operating between room temperature and liquid nitrogen temperature. The data are presented in terms of both heat flux and apparent thermal conductivity (k-value). Values of 0.87 W/m^2 and 0.029 mW/m-K are reported for an insulating vacuum of 0.0015 Pa. The tests were conducted at cold vacuum pressures from high vacuum to soft vacuum. Heat transfer was about 60 times greater at the degraded vacuum of 13.33 Pa. Complete temperature profiles through the material layers were also measured for all 10 vacuum levels.

The study was representative of an actual use cylindrical configuration with folded seams. Practical information on the handling, installation, and evacuation indicates that this insulation system is well suited to large-scale cryogenic applications that require high-level performance. The driver for high performance may be the heat leak itself, as in the case of LHe cryostats, or the economics of preservation of cryogens, as with commercial industrial equipment. However, one must remember that these laboratory data are under ideal conditions and are not necessarily achievable in practice. Materials, number of layers, packing factor, and methods are all important parameters in actual MLI performance.

Heat transfer studies and practical methods of application of high performance MLI blankets continue to be addressed at the Cryogenics Test Laboratory at NASA Kennedy Space Center. The target is to develop thermal insulation systems that can operate effectively for large-scale energy-efficient industrial application on Earth and in space.

REFERENCES

1. Lebrun, P., Advanced superconducting technology for global science: the Large Hadron Collider at CERN, Advances in Cryogenic Engineering (2000), 47 3-14
2. Fesmire, J. and Augustynowicz, S., Insulation testing using cryostat apparatus with sleeve, Advances in Cryogenic Engineering (2000), 45 1683-1690
3. Augustynowicz, S. and Fesmire, J., Cryogenic insulation system for soft vacuum, Advances in Cryogenic Engineering (2000), 45 1691-1698
4. Darve, C., et al., Thermal performance measurements for a 10-meter LHC dipole prototype (Cryostat Thermal Model 2), Internal report, LHC-Project-Note-112 (1997)
5. Dufay, L., et al., A large-scale test facility for heat load measurements down to 1.9 K, Advances in Cryogenic Engineering (2000), 47 98-105
6. Mazzone, L., et al., Measurements of multi-layer insulation at high boundary temperature, using a simple non-calorimetric method, International Cryogenic Engineering Conference, Grenoble, July 2002
7. Keller, C., Cunnington, G., and Glassford, A., Final Report: Thermal performance of multilayer insulations, NASA CR-134477 (1974), 4-16 to 4-44
8. Shu, Q., et al., An experimental study of heat transfer in multilayer insulation systems from room temperature to 77 K, Advances in Cryogenic Engineering (1986), 455-463
9. Fesmire, J. and Augustynowicz, S., Thermal performance of cryogenic piping multilayer insulation in actual field installations, Seventh Cryogenics 2002 IIR International Conference, Praha, Proceedings (2002) 94-9