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A calorimeter for multilayer insulation (MLI) performance measurements at variable temperature

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ABSTRACT

Here we describe a concentric cylindrical calorimeter with radiation guards developed to measure the thermal performance of multilayer insulation (MLI) for low temperature applications. One unique feature of this calorimeter is its ability to independently control the boundary temperatures between room temperature and about 15 K using two single-stage Gifford–McMahon cryocoolers. Also, unlike the existing calorimeters that use the evaporation rate of a liquid cryogen to measure the heat load, in the present system the total heat transfer through the MLI is measured by recording the temperature difference across a calibrated heat load support rod that connects the cold inner cylinder to the lower temperature cryocooler. This design allows the continuous mapping of MLI performance over a much wider temperature range with independently controlled boundary conditions. The calorimeter is also suitable for performing a variety of radiation heat transfer experiments including the determination of the temperature dependence of the total emissivity.

1. Introduction

Multilayer insulation is the most effective means of reducing heat load due to radiation in cryogenic systems. As a result, it has found applications in variety of low temperature systems from ground based storage of liquid propellants for spacecraft support to superconducting systems such as for magnetic resonance imaging or particle accelerators. The performance of MLI blankets depends strongly on the configuration such as number of layers, layer density per unit thickness, material properties and interstitial gas pressure within the blanket. This fact strongly suggests that the performance of a specific blanket configuration with different temperature boundary conditions should be measured before it is used in an actual system.

A literature survey on the available calorimeter designs suitable for MLI performance measurement indicates that nearly all the calorimeters use the rate of evaporation of a cryogen to obtain the performance of an MLI blanket. Typical examples of such systems are described by [6,1], and [4]. In these systems, the cold boundary temperature is maintained by a suitable cryogen at saturated conditions while the warm boundary temperature is controlled at some higher temperature either by a higher boiling point liquid or by utilizing heaters. The heat load through the MLI blanket due to radiation causes the cryogen to evaporate. Either the vapor mass flow rate or the change in the mass of the stored cryogen due to evaporation is then measured to determine the heat load.

The main drawback with the rate of cryogen evaporation technique is that the MLI performance can be measured only between the saturation temperature of the available cryogens and some higher temperature that is often room temperature. Additionally, the vapor flow rate measurement may be prone to errors particularly when the flow rates are small or large changes in the vapor density occur due to temperature fluctuations.

Many superconducting systems utilize MLI in different temperature ranges owing mainly to the growing tendency to avoid boiling cryogens for shield cooling and ready access to reliable cryocoolers. These applications have stimulated interest in the performance MLI at intermediate temperatures, a demand that has resulted in the development of test facilities capable of measurements between temperatures other than saturation of cryogens [5,3]. The one of these facilities developed in our laboratory and described here is based on a concentric cylindrical calorimeter that utilizes two single-stage-cryocoolers (or alternatively a single two-stage-cryocooler) to maintain the cold and warm boundary temperatures. The use of cryocoolers allows the measurements at any set of boundary temperatures and for large or small temperature difference. This innovative design is based on a measurement of the temperature gradient along a calibrated heat load support rod that also supports the cold cylinder, thus eliminating the potential problems associated with the vapor flow rate

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measurements technique. A similar device was also developed in our laboratory for measurements of the low temperature thermal conductivity of solid foam insulation [2]. The details of the present calorimeter design and performance are discussed in the following sections.

2. Calorimeter description and instrumentation

The calorimeter is of the concentric cylindrical type and is in the vertical orientation. The entire calorimeter is suspended below a room temperature top flange and inside a vacuum jacketed cryostat. The cryostat has a liquid nitrogen shield that can be filled to improve the vacuum and reduce the load on the cryocoolers when performing measurements at the lowest temperatures, Fig. 1. The warm and cold cylinders, both made of copper, are supported by two separate copper support plates. The warm cylinder support plate is suspended from the top flange via G-10 rods, while the cold cylinder support plate is suspended from the warm cylinder support plate also via a separate set of G-10 rods. The warm cylinder is bolted on the warm cylinder support plate while the cold cylinder is suspended from the cold cylinder support plate via the cold cylinder support rod. The ends of the cylinders are capped with copper plates. There are two guard radiation shields on either end of the cold cylinder that are supported from the cold cylinder support plate via copper rods. These shields are controlled at the

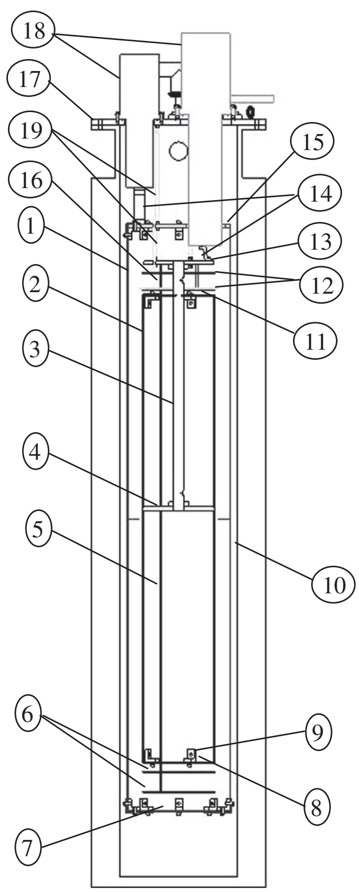

Fig. 1. Schematic of the calorimeter: 1 – warm cylinder, 2 – cold cylinder, 3 – cold cylinder support rod, 4 – cold cylinder support plate, 5 – lower radiation shield support rod, 6 – lower radiation shield, 7 – warm cylinder end cap, 8 – cold cylinder end cap, 9 – support bracket, 10 – cryostat/vacuum vessel inner wall, 11 – warm cylinder end cap, 12 – upper radiation shield, 13 – upper cold cylinder support plate, 14 – flexible link, 15 – warm support plate, 16 – upper radiation shield support, 17 – room temperature top flange, 18 – cryocooler, and 19 – suspension rod.

cold cylinder temperature to eliminate end effects to the measurement. Thus all heat flowing from the outer to the inner cylinder passes through the MLI blanket.

The major components and their dimensions are as follows: The cold cylinder is made of 191 mm outside diameter, 1219 mm long and 3.2 mm thick copper pipe while the warm cylinder is made of 2.3 mm thick copper sheet rolled into a 272 mm diameter, 1524 mm tall cylinder. The ends are closed with copper flanges also made of copper sheet 2.3 mm thick. The gap between the two cylinders is 38 mm. Since the MLI is wrapped around the cold cylinder, these dimensions translate to an active heat transfer area, as defined by the surface area of the inner cylinder, of 0.73 m^2. This configuration results in a slight increase in surface area of the MLI as the circumference of the material increases through the blanket. However, typical MLI blankets tested in this apparatus have a build of between 2 and 5 mm resulting in less than a 5% increase in the surface area through the blanket. Results discussed below are all referenced to the inner cylinder area to be consistent and because the thickness of the blankets vary. This gives a slightly more conservative value as compared to the area calculated on the basis of the mean area at the mid-point of the blanket.

The cold cylinder support rod is a solid metal piece threaded at both ends so that it can attach the upper cold cylinder support plate to the cold cylinder support plate located at the mid-plane of the cold cylinder. This rod is 25.4 mm diameter and 657 mm long and has two temperature sensors located near each end. The rod can be made of different materials based on the desired temperature gradient for a given heat load. In the results presented here, the support rod is made from OFHC copper.

Two GM type cryocoolers, thermally linked to the support plates via flexible copper braids, provide the cooling power to the copper cylinders. A total of fourteen Lakeshore CX-1070 thermometers with a typical resolution of ±16 mK at 77 K are placed at various locations on the calorimeter. These thermometers are CU packaged; that is embedded in copper bobbins for better thermal contact and configured for four wire measurements. In addition to the two thermometers on the cold cylinder support rod, other thermometers on the calorimeter are as follows: warm cylinder support plate and cold cylinder support plate have one thermometer each; cold cylinder support rod has two thermometers; cold cylinder and warm cylinders have two thermometers each; two end caps closing the cold cylinder have one thermometer each; warm cylinder bottom end cap has one thermometer (top is closed with the support plate, which has a thermometer); radiation shields that are closer to the cold cylinder on either side have one thermometer each.

The temperatures of the cold and warm cylinders, i.e. boundary temperatures, are controlled by electronic temperature controllers (Lakeshore Cryotronics model 340), which utilize the heater and thermometer couples on the support plates and the radiation shields. The heaters are film type with Kapton backing material (Minco, Inc.). A turbomolecular pump is used to create and maintain the vacuum inside the cryostat. The vacuum level is typically maintained below 10^{-5} mbar and monitored using an Edwards wide range vacuum gage mounted on top of the cryostat. It is also possible to fill the liquid nitrogen shield of the cryostat to reduce the radiation heat transfer and improve the vacuum. This is typically done when the warm boundary temperature is well below room temperature.

3. Instrument calibration

Measurement of the heat load to the inner cylinder depends on knowing the temperature difference along the inner cylinder support rod as a function of total heat load, Q. With the known