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Research paper

Cryogenic thermal conductivity measurements on candidate materials for space missions

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ABSTRACT

Spacecraft and instruments on space missions are built using a wide variety of carefully-chosen materials. It is common for NASA engineers to propose new candidate materials which have not been totally characterized at cryogenic temperatures. In many cases a material's cryogenic thermal conductivity must be known before selecting it for a specific space-flight application. We developed a test facility in 2004 at NASA's Goddard Space Flight Center to measure the longitudinal thermal conductivity of materials at temperatures between 4 and 300 K, and we have characterized many candidate materials since then. The measurement technique is not extremely complex, but proper care to details of the setup, data acquisition and data reduction is necessary for high precision and accuracy. We describe the thermal conductivity measurement process and present results for ten engineered materials, including alloys, polymers, composites, and a ceramic.

1. Introduction

Many of NASA's scientific space missions include instruments which operate at cryogenic temperatures. For these missions, both the spacecraft and the instruments are built using materials specifically chosen for optimum performance. They must all survive the launch and the space environment, and some have additional requirements on their thermal conductivity. Structural elements must be stiff and strong, but they must not conduct excessive heat from the warm to the cold parts of the spacecraft. Electrical cables must provide wires with appropriate electrical resistance, and they must include sufficient insulation and shielding. However, when these cables run from a room-temperature electronics box to a cryogenic instrument, they must not conduct more heat than the cooling system can handle. Thermal radiator backing plates must be structurally sound and have very high thermal conductivity. In general, all objects on a NASA mission must be as light as possible. Projects often identify engineered materials, such as alloys, polymers and composites, as candidates to meet these requirements, based on known room temperature properties. As a result, NASA often finds itself in need of thermal conductivity data on materials at cryogenic temperatures.

In support of the James Webb Space Telescope (JWST), we developed a test facility in 2004 at NASA's Goddard Space Flight Center to measure the thermal conductivity of materials between 4 and 300 K. These measurements are longitudinal, meaning that they determine the conductivity of heat along a significant length of material rather than normal to the plane of a thin material sheet. Nearly all of the thermal conductivity measurements that JWST needed were longitudinal.

The thermal conductivity, κ, is generally a function of temperature, and its MKS units are W/m/K. The general approach to measuring κ is to cause heat to flow through a constant-cross-section sample and determine the temperature gradient. To get high-precision thermal conductivity data, we chose to perform absolute measurements. This is in contrast to comparative methods, in which calibrated thermal conductance standards are installed in the test set-up along with the sample to be characterized. In one such comparative approach, the sample is located between two standards, to which it is thermally linked in series [1]. Heat flows through this assembly, and the temperature drop across the sample is compared to the drops across the standards. The ratio of these temperature drops is inversely proportional to the ratio of thermal conductances, so the sample's thermal conductivity can be determined.

For high-precision measurements, this comparative approach poses some problems. The standards must have been characterized to at least as high precision as that desired for the sample measurement. In addition, they must have conductances reasonably close to that of the sample (which is initially unknown). A mismatch in these conductances increases the uncertainty in backing out the sample conductance, and at higher temperatures it stymies efforts to limit the heat loss via thermal radiation. Nearly all candidate materials for use as a standard have batch-to-batch thermal conductivity variations of at least a few percent in the cryogenic temperature range. That suggests that in most cases a custom absolute thermal conductance measurement must be done

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ahead of time on each standard, with significant cost and logistical impact. For high-precision data it makes sense to perform an absolute measurement on the sample itself.

We chose an approach which has been described elsewhere [2]. Our specific implementation of this approach has also been described before [3,4], but we have improved details of the setup, data acquisition and data reduction over time. Since developing our test facility, we have characterized many materials for JWST and other programs. Our goal here is to both share the thermal conductivity data and to provide guidance to other researchers who may wish to perform similar measurements themselves.

2. Measurement challenges

Most absolute thermal conductivity measurements involve establishing steady "thermal balance" states in a sample having uniform cross sectional area along its length. In each such balance, heat is generated in a resistive heater mounted on the "floating" end of the sample. The applied power is the product of the electrical current flowing through the heater and the voltage drop across it, both of which can be measured to very high precision by standard multi-meters. The sample's other end is thermally attached to a heat sink referred to as the "base," at a slightly lower temperature. An idealistic assumption is that the sample exchanges no heat with its surroundings, and only conducts heat from the heater to the base. If this were the case, in this steady state, with a small temperature drop across the sample, it would be true to a very close approximation that

$$\kappa(\overline{T}) = \frac{L\dot{Q}}{A\Delta T}. \tag{1}$$

Here $\dot{Q}$ is the conducted heat, $\overline{T}$ is the average of the temperatures at the two sample ends, ΔT is the difference between these temperatures, L is the sample length, and A is the sample's cross-sectional area. Assuming that a researcher can install and operate compact heaters and thermometers, it might seem that an absolute thermal conductivity measurement is a straightforward endeavor. One simply measures the sample's end temperatures and the corresponding heater power, and Eq. (1) gives the thermal conductivity at the average temperature. Fig. 1 is a schematic representation of the basic set-up for this approach. Note that an isothermal can, attached to the base, surrounds the sample to eliminate thermal radiation heat exchange with nearby surfaces at much higher or lower temperatures.

Unfortunately, there are a number of complications involved in this approach. Some of them will seem obvious and easily-solvable to experienced cryogenic researchers. Others are only important for high-precision measurements. However, a perusal of the literature has shown that some researchers are ignoring each of these issues in their attempts to measure thermal conductivity. We have found that only a modest amount of extra effort is needed to address these issues, so we will discuss all of them here.

First, the heat conducted through the sample, $\dot{Q}$, is not equal to the measured heater power, $\dot{Q}_H$. Some heat is conducted away from the sample's floating end via the thermometer's electrical leads. The heater's leads present a more complicated issue, as they carry significantly more current than those of the thermometer. Ohmic heat is generated in these leads, and in some cases a fraction of this heat is conducted into the heater itself. Thus, the net heat conducted away from the heater via its leads may end up being either positive or negative.

At higher temperatures, a significant amount of heat passes directly from the heater and sample to the base and its can via thermal radiation. It may seem that this issue can be mitigated by always using small ΔT values across the sample, but this is not true. The radiative heat exchange between two objects at different temperatures, T_{Hot} and T_{Cold}, is proportional to $T_{Hot}^4 - T_{Cold}^4$. However, for small values of $\Delta T = T_{Hot} - T_{Cold}$, it is easy to show that

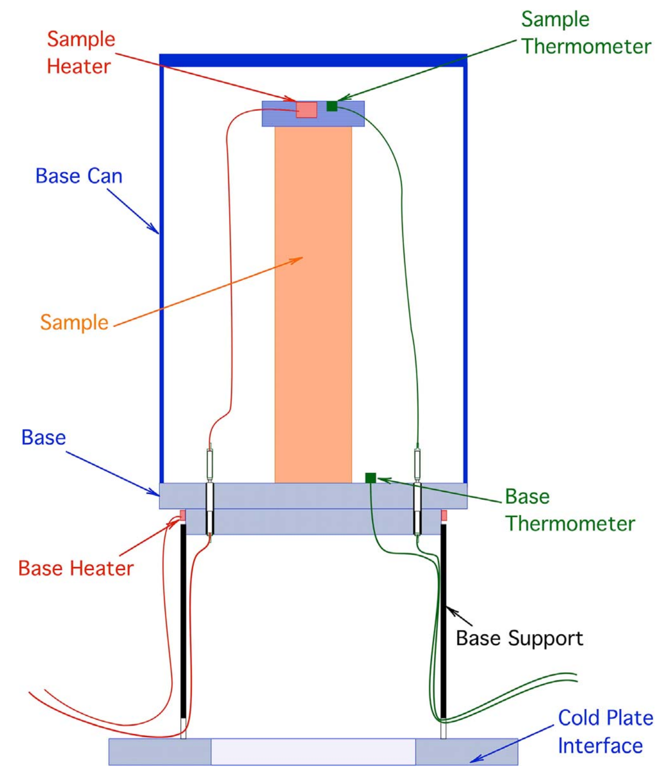

Fig. 1. A schematic representation of a basic thermal conductivity measurement apparatus. There are problems with this approach which make it inappropriate for high-precision measurements.

$$T_{Hot}^4 - T_{Cold}^4 \sim 4\overline{T}^3\Delta T, \tag{2}$$

where $\overline{T}$ is the average of the two temperatures. This approximation becomes more accurate as ΔT decreases relative to $\overline{T}$. Thus, for small ΔT values, the heat radiated from any location on the sample to its surroundings at the base temperature is proportional to ΔT, as is the heat conducted through the sample. For any given average temperature, this radiated heat will give the same relative error in the thermal conductivity measurement, independent of ΔT.

The most convenient locations for thermometers in such an experiment are generally on the base and on the sample's floating end heater assembly, as shown in Fig. 1. However, the indicated total temperature drop is then not equal to the temperature drop across the sample. There are thermal joint resistances associated with the heater's attachment to the floating end and the sample's attachment to the base. Since heat flows through these joints, there is a localized temperature drop across each of them, and the indicated total ΔT includes these temperature drops. In addition, the temperature indicated by a thermometer has an error, δT, at any temperature due to scatter in its temperature vs resistance calibration curve.

The issues listed here result in uncertainties in the power flowing through the sample and the temperature drop across it, leading to a significant uncertainty in the thermal conductivity. We describe below a configuration which drastically reduces the magnitude of several of these uncertainties and a data acquisition and analysis approach which makes the remaining ones nearly irrelevant.

3. Measurement set-up

Fig. 2 shows our measurement configuration roughly to-scale, with a sample length of about 9 cm. It is installed on the cold plate of a cryostat and surrounded by a nearly-isothermal cold plate shield. The cold plate is cooled to temperatures as low as 3 K by a standard two-stage cryocooler. The sample bottom is clamped to a copper base, which