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The dual-mode heat flow meter technique: A versatile method for characterizing thermal conductivity

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ABSTRACT

The dual-mode heat flow meter technique was developed for steady-state thermal characterization by optimizing the curve fit between the experimental temperature profile and the prediction from a simple analytical solution taking into account conductive as well as radiative heat transfer. The validation results were seen to be in good agreement with published literature values and demonstrated the versatility of the method. Moreover, the technique is ideally suited for characterization of anisotropic materials without necessitating any additional information about the nature of anisotropy and lends itself as an attractive alternative for characterization of novel materials with engineered transport properties.

1. Introduction

Efficient and accurate thermal characterization is critical to the continued development of materials with engineered thermal transport properties for applications such as thermal management, thermoelectrics, thermal insulation and more. Thermal characterization techniques should be simple and reliable despite being constrained by the unpredictable nature of the materials being tested. For instance, the measurements should not be affected by the fragility of the samples, their unexpectedly extreme thermal properties (either very low or very high), their constrained geometries, and most importantly, their limited availability. Conventional steady-state thermal conductivity measurement techniques like the heat flow meter [1] are simple and easy to use but have been limited to certain ranges of the spectrum of thermal conductivity, often require specific geometries for testing, and even minor heat losses can significantly influence accuracy. In contrast, transient techniques, such as laser-flash or transient hot-strip, are known to be reliable over the entire range but conductivity measurements typically involve relatively complicated data analysis and are contingent upon the accurate determination of specific heat capacity and density [2,3]. Additionally, most conventional techniques, namely laser-flash or three-omega, may only provide an effective thermal conductivity when used for characterizing materials with anisotropic thermal properties unless modifications are applied [2,4]. Thus, a simple and versatile characterization technique that is capable of measuring the thermal conductivity in a particular direction without requiring any knowledge or assumption about the properties in the other directions is desirable.

In this work, we report on a steady-state thermal characterization technique which can be used for measurement of insulators as well as conductors and is particularly suitable for thin, anisotropic materials. In essence, the method was developed from the standard ASTM C 518 based heat flow meter technique [1], which compares the steady-state temperature gradient in the sample to that of a reference material to determine the thermal conductivity of the unknown sample. The conventional heat flow meter technique assumes one-dimensional conduction to be the only mode of heat transfer and works very well for determining through-thickness thermal conductivity of thin thermal insulators as long as the requirement that one-dimensional heat flow with negligible losses is strictly maintained. The validity of the assumption for one-dimensional conduction to be the only mode of heat transfer relies on using test specimens that are short along the direction of heat flow and have a large cross-section. This works very well for low thermal conductivity materials [5,6]. Owing to their short length, the surface area available for convection and/or radiation heat losses from the test specimen becomes negligible compared to the large cross-section available for conduction heat transfer through the specimen. Alternatively for highly conductive materials, establishing a measurable temperature drop is critical and therefore longer specimens may be required for the measurement. However, due to a large surface area, the effects of convection and radiation may no longer be negligible, thereby casting doubt on the reliability and accuracy of the technique. Previous works on use of

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Nomenclature

A	area of cross-section of sample
A_{Cu}	area of cross-section of the copper reference
A_s	surface area of sample
$A_{s_{Cu}}$	surface area of the copper reference
Bi	Biot number
Bi_r	Biot number for radiation
h_r	coefficient of radiation heat transfer from sample
$h_{r_{Cu}}$	coefficient of radiation heat transfer from copper reference
k	thermal conductivity of sample
k_{Cu}	thermal conductivity of copper reference
L	length of sample
L_c	characteristic length
L_{Cu}	length of copper reference
P	perimeter of sample
Q	total heat flow
Q_c	heat flow due to conduction
Q_r	heat flow due to radiation
R_c	resistance to conduction heat transfer
R_r	resistance to radiation heat transfer
T	temperature
T_{avg}	average temperature
$T_{avg_{Cu}}$	average temperature of copper reference
T_{ce}	cold end temperature
T_{he}	hot end temperature
T_∞	ambient temperature
t	thickness
w	width
x	Cartesian coordinate along the direction of conduction heat transfer

Greek symbols

ΔT	temperature difference in sample
ΔT_{Cu}	temperature difference in copper reference
Δx	distance between two points on the sample
Δx_{Cu}	distance between two points on the copper reference
ε	emissivity of sample
ε_{Cu}	emissivity of copper
σ	Stefan–Boltzmann constant
ω	dimensional ratio of heat transfer due to radiation and conduction

Subscripts

avg	average
Cu	copper
ce	cold end
he	hot end
r	radiation
s	surface
∞	ambient

Subscript to subscripts

Cu	copper

the standard technique did not consider the effects of the convection and/or radiation losses [5–7], perhaps because the heat flow meter had primarily been used for testing materials with thermal conductivities less than ~20 W/m-K [5,6]. More importantly, these materials had provided the researchers with a test specimen such that the thickness and width were larger compared to the length in the direction along which the thermal conductivity was desired to be estimated. However, a situation where such a specimen may not be obtainable is likely, especially with the widespread research on novel composite materials, including nanocomposites. In other words, it is likely that a material could be thin and anisotropic while being required to be tested for thermal conductivity in the direction perpendicular to its thickness. To overcome these obstacles, the dual-mode heat flow meter, which considers both conduction and radiation modes of heat transfer along a specimen of relatively long length was conceived to broaden the applicability of the heat flow meter technique while maintaining its inherent simplicity. This technique accurately and reliably measures thermal conductivity along the direction of one-dimensional heat flow. Convection heat loss can be minimized by conducting the experiments under conditions of very high vacuum (pressures less than 10^{-5} Torr).

2. Experimental details

The typical experimental configuration of the dual-mode heat flow meter includes a thin specimen (~5 mm × ~50 mm, width × length) in line with and contacting a reference material of similar width as shown schematically in Fig. 1. The sample and the reference material were held together by two pieces of thin kapton tape (~65 µm thick) that were of similar width as the specimen. Please note that only a diagrammatic representation is used for describing the arrangement of the sample and the reference material; as the underlying assumptions (discussed later) necessary for this method can be achieved with various experimental arrangements, all differing slightly from one another. Copper (Alloy 110 ASTM B-152) having a thermal conductivity of 388 W/m-K was used as the reference material for the purpose of this work, but other materials may be equally suitable. All the test specimens used in this work were about 1 mm in thickness, which ensured that the temperature remains uniform at each cross-section at a particular location along the length of the test specimen. Two small strip heaters (~15 mm wide) were placed above and below the copper strip at one end. The entire assembly was suspended between clamps mounted on two end supports and then placed inside a bell-jar vacuum chamber (15 inches in diameter and 18 inches in height) such that the test specimen is ~4 inches above the base plate. It is worth noting that a vacuum environment serves to keep heat losses from the specimen to a minimum as it not only avoids convection but also prevents heat conduction which would adversely affect the experiment if the test specimen was merely surrounded by another insulating material. The conduction into the insulation would be particularly significant if the material to be tested is also a thermal insulator. The stainless steel base plate (21 inches in diameter and 0.5 inches in thickness) of the vacuum chamber was in thermal contact with the end

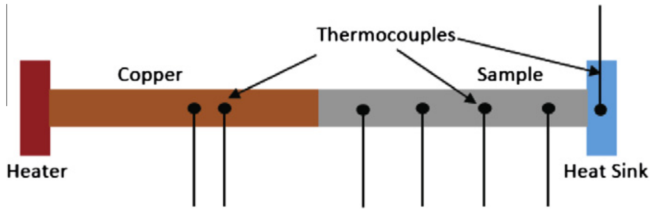

Fig. 1. Schematic of the experimental setup for the dual-mode heat flow meter technique. The thermocouple used for measuring the ambient temperature is not shown in the schematic.