International Journal of Thermal Sciences 77 (2014) 165–171

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Computational study on anisotropic thermal characterization of multi-scale wires using transient electrothermal technique

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A R T I C L E I N F O

Article history:
Received 21 June 2013
Received in revised form
22 October 2013
Accepted 25 October 2013
Available online 6 December 2013

Keywords:
Carbon nanotube
Nanowire
Anisotropic heat transfer
Radiation heat loss
Transient electrothermal technique
Finite difference method

A B S T R A C T

Numerical models predicting anisotropic heat transfer of multi-scale wires using the transient electrothermal (TET) technique were successfully developed. Compared to previous models, the developed models are more realistic and accurate by taking into account the anisotropic thermal conduction in both axial and radial directions and the radiation heat loss from the wire surface to the measurement ambient. In the TET technique, the to-be-measured wire is placed between two electrodes. By feeding a step DC to the wire, its temperature increases and eventually reaches the steady state. The temperature evolution is probed by measuring the variation of voltage/resistance over the wire, which is then used to determine the axial and radial thermal diffusivities of the wire. For the first time, the developed models are solved using implicit finite difference method, giving more accurate predictions than the previous models using Green's function. The obtained results are in excellent agreement with the experimental data. Using the validated models, the effects of various wire morphologies (radius of 10–200 μm, length of 5–20 mm), and experimental conditions (DC supply of 5–50 mA and ambient temperature of 0–25 °C) on the thermal characterization of the wires were also quantified. Our results are beneficial to experimentalists on optimization of measurement conditions of the experiments characterizing the thermal properties of multi-scale wires such as carbon-based microfibers.

1. Introduction

In order to promote potential engineering applications of micro/nanoscale materials, tremendous efforts have been put into research to understand better the fundamental properties of micro/nanoscale materials. However, the research of thermal transport in the micro/nanoscale structures has been crucial. Several techniques [1–6] have been developed to study thermophysical properties of wires/tubes at micro/nanoscale, such as the 3ϖ method [1,2,5,6], the pulsed laser-assisted thermal relaxation (PLTR) technique [3] and the transient electrothermal (TET) technique [4]. The 3ϖ method was first developed to replace conventional techniques [7–19] and measure thermal properties of carbon nanotubes (CNTs) and thin films at micro/nanoscale. By minimizing heat loss on measuring probes, experimental results can be more accurate.

Compared to the 3ϖ method, the TET technique produces a higher signal to noise ratio and the experiment time is significantly reduced. Moreover, the TET technique can be used to measure thermophysical properties of conductive, semiconductive, and nonconductive wires. The PLTR technique has been developed subsequently but still have some limits compared to the TET technique. In the PLTR technique, pulse laser with duration of several nanoseconds is used to heat the to-be-measured wire. However, due to the laser reflection at the wire surface and laser transmission through the wire, the thermal energy absorbed by the sample is difficult to be determined in the PLTR technique. When measuring the thermal conductivities of semiconductive and nonconductive wires, thin films are coated on the wire to make the samples conductive and hence, the laser reflection on the wire surfaces will increase due to the coated metal thin films on the wires [3]. In addition, the thermal heating of the supply current in PLTR technique is ignored which will result in some inaccuracies of the measured results [3]. Moreover, laser equipment used in the PLTR technique is normally expensive and the experiment systems are always relatively complex. Due to these limitations and inaccuracies of the 3ϖ method and the PLTR technique, the TET technique is more preferred in this work.

In the TET technique [4], sample wire is suspended between two electrodes as shown in Fig. 1. Heat loss to the ambient through convection in vacuum environment is ignored. When experiment

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http://dx.doi.org/10.1016/j.ijthermalsci.2013.10.018

Nomenclature

c_p	specific heat capacity (J/kg K)
k_r	radial thermal conductivity (W/K m)
l	dimensionless length
L_0	length (m)
q_{loss}	heat loss flux (W/m^2)
$\dot{Q}$	heat generation rate (W/m^3)
r	radius (m)
r_0	maximal radius of wire (m)
R	dimensionless radius
R_e	electric resistance (Ω)
T_∞	ambient temperature (K)
T	maximal temperature (K)
T_{r_0}	wire surface temperature (K)
x	axial parameter (m)

Greek symbols

α_x	axial thermal diffusivity (m^2/s)
α_r	radial thermal diffusivity (m^2/s)
ρ	density (kg/m^3)
σ	Stefan–Boltzmann constant (W/m^3 K^4)
θ	dimensionless temperature
θ_{r_0}	dimensionless temperature at surface
τ	dimensionless time

starts, a step DC is supplied to the wire to introduce electrical heating. Upon heating, the temperature of the sample wire will increase and eventually reach the steady state. The time required to reach the steady state strongly depends on the morphologies and thermophysical properties of the wires. With same thermophysical properties and experimental conditions, a longer wire requires a longer time to reach the steady state. Similarly, with same wire length and experimental conditions, a wire with a larger thermal diffusivity/conductivity will take shorter time to reach its steady thermal state. The temperature evolution during the heating process can be probed by measuring the voltage/resistance variation over the wire [4].

Guo et al. [4] applied the TET technique to measure the thermal diffusivities of single-wall carbon nanotube (SWNT) bundles and polyester fibers. A 25.4 μm thick platinum wire was used as the reference sample to verify this technique. The thermal diffusivities of SWNT bundles obtained from the temperature change profile were determined by applying linear fitting at the initial stage of electrical heating when $0 < t < \Delta t$, where Δt is very small and the temperature gradient along the wire is also small. The temperature change with time was described as $\Delta T = q_0/\rho c_p \Delta t$, where q_0, ρ and c_p are the heat generation rate per unit volume, the density and specific heat capacity of the wire, respectively. However, the existing models of Guo et al. [4] were solved by Green's function, which only considered one-dimensional (axial direction) heat transfer and ignored the radial heat conduction and heat loss through radiation to the ambient. Due to the model assumptions and the limits of the Green's function, these models used in Guo et al.'s work might not predict accurate thermal conductivities of SWNT bundles and polyester fibers [5].

In this paper, modified computational models were developed. The developed models eliminate several model assumptions of previous works by taking into account the anisotropic heat transfer and the radiation heat loss from the wire surface to the experimental ambient. Using an implicit finite difference method to solve the developed models is more powerful than the integral of Green's function [5]. As the developed models consider heat transfer in both axial and radial directions, as well as heat loss from surface of the wire through radiation, the heat transfer phenomena and the temperature distribution in the wire are more accurately predicted. Implementing global fitting method to analyze the temperature evolution, more accurate thermophysical properties of the to-be-measured wires can be derived. To validate our developed models, experimental data of SWCNT bundles [4] were used only due to the limitation of experimental data. The simulation results gave a better agreement with the experimental data than Guo et al.'s models [4]. For helping experimentalists to optimize their measurement conditions, effects of various wire morphologies (radius of 10–200 μm, length of 5–20 mm) and experimental conditions (DC supply of 5–50 mA and ambient temperature of 0–25 °C) on the heat transfer characteristics of multi-scale wires were also quantified by using our validated models.

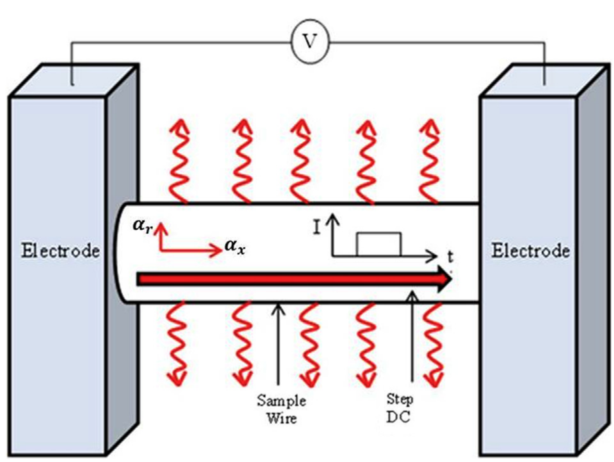

Fig. 1. Schematic of the transient electrothermal (TET) technique principle and the developed anisotropic heat transfer model with heat loss. The to-be-measured sample wire is suspended between two electrodes, a step DC is fed to the sample to provide electrical heating. The temperature evolution is probed by measuring the variation of voltage over the wire.

2. Computational model development

There have been several physical models developed in previous studies to derive the thermal diffusivity of micro/nanoscale wires using the temperature evolution history generated from experiments [3–5]. In order to make reported models more realistic, and thus more accurate, our developed models considered the heat transfer both in axial direction and in radial direction as well as the heat loss to the ambient through radiation.

A schematic configuration of the physical model considered in this study is shown in Fig. 1. The wire is mounted between two electrode blocks and a step DC is supplied to introduce electrical heating of the wire. During the heating process, heat is considered to be transported in both radial direction and axial direction, and due to the vacuum ambient, heat is only lost to the ambient through radiation from the surface (denoted by arrows in Fig. 1). In the figure, α_x and α_r denote the axial and radial thermal diffusivities, respectively.

Considering the geometry of micro/nanoscale wires, the cylindrical coordinate system was adopted. The transient heat equation for the anisotropic model in cylindrical coordinate, can be written as: