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Computational/analytical study of the transient hot wire-based thermal conductivity measurements near phase transition

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ABSTRACT

The performance of the commonly-used transient hot wire technique for measuring the thermal conductivity of materials near their liquid-solid transition point is reported in this paper. Adopting a 1-D transient formulation, the computational methodology is discussed in detail and predictions of the wire temperature are compared to the limiting analytical solutions without and with phase change. By varying the initial solid-state temperature of an eicosane sample, six cases which undergo phase change to different extent were studied. The results exhibit a monotonic dependence of the predicted thermal conductivity value on the initial temperature of the solid medium. As the initial temperature of the solid-state sample approaches the melting point, the predicted thermal conductivity value moves toward the value of the liquid eicosane. Recommendations were provided for performing measurements of thermal conductivity using the transient how wire technique involving phase change.

1. Introduction

Experimental techniques are widely used for determination of the transport properties of materials, such as thermal conductivity and viscosity. These techniques are based on the fundamental relations that govern how the value of the pertinent flux (heat, momentum, etc.) relates to the gradient of the relevant quantity (temperature, velocity, etc.). For instance, both the steady-state and transient techniques that are used for determination of thermal conductivity utilize the Fourier's Law. The transient hot wire (THW) technique that is now widely used for determination of the thermal conductivity of gases, liquids, pastes, etc., has its roots in an ideal limiting case of a transient heat conduction problem [1]. In this formulation, an extremely thin wire of infinite length with a high thermal conductivity is surrounded by a homogeneous material that extends in the radial direction away from the wire to infinity. Upon heating the wire for a short time period, the transient signature of the wire's temperature is utilized to obtain the thermal conductivity of the surrounding material. The pertinent relation among the various governing parameters will be discussed below. Assael et al. [2] has discussed the historical evolution of the transient hot wire technique starting from 1780 up to 2010.

Corrections to the transient hot wire technique that address deviations from the idealized formulation have also been developed. Nine (9) such modifications that account for effects of finite inner cylinder (heated wire), composite cylinders, the Knudsen effects, radiation, required condition at the outer cell circumference, the role of compressibility and natural convection, finite cell dimensions, variable fluid properties and the correction for finite length of wire were addressed in detail by Healy et al. [3]. Nagasaka and Nagashima [4] developed a new design of an instrument based on the transient hot wire technique by coating the platinum wire with a thin electrical insulation layer made of polyester 2. Through this modification, the capabilities of the instrument were broadened to include electrically-conducting fluids. Until that time, the bare metallic wire within the instrument was only compatible with electrically non-conducting media. The analytical solution considering the effects of the insulation layer on the temperature rise of the metallic wire was then discussed extensively. As a case study, thermal conductivity values of an aqueous NaCl solution was measured successfully with an accuracy of ±0.5%.

In recent years, operational deviations from the idealized case [1] have been treated computationally to include the above-mentioned or other effects, whereby analytical relations are replaced with numerical solutions of the governing differential equations, e.g. Assael et al. [5], Duluc et al. [6] and Rusconi et al. [7]. Assael et al. [5] used a numerical finite-element method (FEM) to solve a set of energy conservation equations which describe the operation of the transient hot wire technique. They showed that the adopted approach was applicable to predicting the thermal conductivity of liquids. The adopted approach

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Nomenclature

a	radius of the wire, mm
b	radius of the cylindrical block, mm
C_p	specific heat, J/kg K
k	thermal conductivity, W/mK
L	latent heat of fusion, J/kg
q	strength of the line heat source, W/m
r	radial coordinate, mm
s	instantaneous position of the liquid-solid interface, mm
t	time, s
T	temperature, K or °C
Greek symbols	
α	thermal diffusivity, m^2/s
ε_T	temperature difference ($T_m - T_i$), °C
γ	Euler's constant, dimensionless
λ	parameter introduced in Eq. (10) or constant of a transcendental equation (11)
ρ	density, kg/m^3
τ_h	time instant of conclusion of heating, s
τ_m	time instant of initiation of phase transition on the surface of the wire, s
Subscripts	
i	initial
l	liquid
m	melting
s	solid
w	wire

considered the essential corrections to the ideal transient hot wire theoretical model which then led to accurate predictions when compared with the experimentally-measured thermal conductivity values. The authors presented computationally-obtained thermal conductivity values vs. measured quantities reported in the literature for Argon at high pressure conditions with an accuracy of ±0.35%. Utilizing the velocity–pressure formulation, spectral methods and domain decomposition technique, Duluc et al. [6] studied 2-D transient natural convection in liquid nitrogen around a pulse-heating thin bronze wire. The numerical data were then compared with their experimental observations. Considering time evolution of the wire's temperature rise, the theoretical heat conduction solution and numerical results were in close agreement during early time steps which indicated a purely conductive heat transfer regime. However, there was an onset time at which natural convection effects became important and thereafter results of the numerical simulation started to diverge from the experimental data. The authors proposed the wire thermal inertia as the key parameter that governs the aforementioned behavior. Rusconi et al. [7] studied the same phenomenon using the FlexPDE finite element method analysis of a 2-D cylindrical model. The Navier-Stokes equations along with the heat transport equation were solved simultaneously in the fluid region. A custom-built setup based on the transient hot wire method was also fabricated and the ensuing measurements of thermal conductivity were tested against results of the numerical simulation. Onset of natural convection effects after a specific time period was clearly observed. In order to exclude convection effects from the thermal conductivity measurements, an operational time scale was quantified. The suggested time-window depends on the dissipated power from the wire and the physical properties of the test fluid. It was also proved that the thickness and the physical properties of the wire insulation layer were such that it will not affect the obtained thermal conductivity values. Adoption of computational techniques to assess variations of the transient hot wire method has also been considered for other measurement techniques. For instance, Rusconi et al. [8] utilized computational fluid dynamics for refinement of thermal-convection effects in the thermal-lensing measurement technique.

Ongoing improvements, maturity and relevance of computational techniques that extend the range of applicability and account for actual physical and operating conditions of thermal conductivity measurements were outlined above. However, no studies that address issues in relation to the performance of the transient methods of measuring the thermal conductivity near the melting temperature of a medium were found. Therefore, computational modeling of the transient hot wire method and assessing its performance and operational issues while melting occurs during the thermal conductivity measurement is reported in this paper.

2. Problem statement

Measuring thermal conductivity of phase change materials (PCM) in their solid-state as a function of temperature using the transient methods, i.e. transient plane source (TPS) and transient hot wire methods, many researchers have studied thermal conductivity values as the reported measurement temperature approaches the melting point of the PCM. Recently, using the transient hot wire method, Wang et al. [9–12] reported experimentally-obtained thermal conductivity values for different phase change materials near their respective melting temperatures. A simple model of the typical reported dependence of thermal conductivity on temperature that assumes constant values of thermal conductivity of the liquid (k_l) and solid (k_s) phases near the melting temperature (T_m) is shown in Fig. 1. As the temperature of the measurement sample approaches the melting temperature, a sharp decline in the thermal conductivity values is registered. Operation of the THW technique under such non-equilibrium condition is not consistent with the idealized theory [1] based on which the transient techniques of measuring thermal conductivity are designed to be applicable. Moreover, the THW technique is ideally-suited to measure the thermal conductivity of a homogenous medium. Therefore, once these conditions break down and the solid PCM starts transforming into two separate phases, the measured thermal conductivity values are not accurate

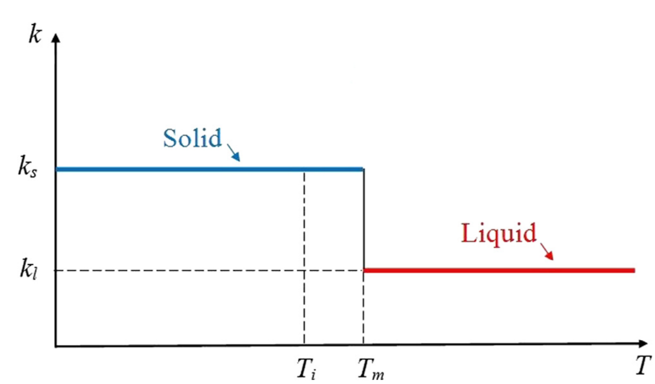

Fig. 1. Schematic diagram of the model of the thermal conductivity variation near the melting temperature.