



Dynamic measurement of the thermal conductivity of phase change materials in the liquid phase near the melting point



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ABSTRACT

This paper deals with the determination of the thermal conductivity of liquid-phase phase change materials (PCMs) near the melting point by studying the evolution process of the solid-liquid interface. A theoretical model was proposed which enables the thermal conductivity to be determined from the displacement characteristics of interface during a melting process. Experiments were performed using a well-designed testing system for two kinds of inorganic PCMs, and the experimental results agreed with the literature values within a range of $\pm 6\%$. The sources of measurement error were studied from the temporal variation characteristics of the experimental results. It is found that the non-ideal boundary conditions of the testing system and the onset of the natural convection were the major causes of the measurement error. To improve the accuracy of the experimental results, numerical techniques were utilized to simulate the melting process of the experiments. The calibrated values of the thermal conductivity were iteratively obtained from the comparisons of interface movement curves between the experiments and simulations, and the discrepancies between the calibrated results and the reference values were limited to $\pm 3\%$.

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1. Introduction

The fundamentals of heat transfer process undergoing solid-liquid phase change near the melting point temperature have been of continuing interest for researchers in the last decades [1]. This is driven by the extremely broad range of applications (i.e. thermal energy storage [2,3], solar energy [4], and passive thermal managements [5]) of phase change materials, due to their high energy storage density and nearly isothermal energy capture/release process [6]. Since the rate of heat transfer and the extent of a phase change process are dependent upon the thermal properties of the PCMs [7], the thermal conductivity of the PCMs near the melting point is a crucial thermo-physical property for the viability of the materials in an engineering application.

For decades, series of measurement techniques have been proposed to determine the thermal conductivity of PCMs [2,8]. Among these testing methods, differential scanning calorimetry (DSC), transient plane source (TPS) and transient hot wire (THW) are widely adopted to characterize the thermal conductivity for PCMs [9] as well as PCMs with thermal-conductive additives [10–12]. However, they are generally aimed at the study of thermal conduc-

tivities of a single phase specimen. The experimental rigs for such methods are expensive, and complicated pretreatments of the specimen are mandatory. Also, it is really difficult to obtain the thermal conductivity of PCM in pure solid or liquid state near the phase change temperature in such tests. This is due to the fact that only small quantities of sample can be analyzed by DSC and TPS, and the phase change behavior of PCMs, i.e. the degree of subcooling and phase segregation, may behave differently from those of the bulk PCMs used in practical applications. It has been noticed by researchers that there exist distinct differences for the values of the thermal conductivities between the solid and liquid state PCMs [13], and this mismatch cannot be filled equivalent by either solid or liquid phase properties since the different molecular arrangement between solid and liquid phase could have a dramatic influence on their thermal conduction behavior [14]. Furthermore, a PCM ideally exists in both its liquid and solid state during a heating/cooling cycle in real applications. Therefore it is of primary importance to obtain the accurate knowledge of the PCMs' thermal conductivities for both phases, especially near the melting point.

To the author's knowledge, only limited investigations were focused on developing measurement techniques to study the thermal conductivity of liquid phase PCM near the melting point. Yin-ping et al. [15] proposed a temperature-history method to determine phase change temperature, thermal conductivity in

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Nomenclature

c_p	specific heat
Fo	Fourier number
H	height of the cylinder
J_0	zero-order Bessel function of the first kind
J_1	first-order Bessel function of the first kind
k	thermal conductivity
L	latent heat
n	number of iterations
R	inner radius of the cylinder
r	radial coordinate
S	source term
Ste	Stefan number
T	temperature
T_0	final wall temperature
T_{ini}	initial wall temperature
T_m	melting temperature
u	fluid velocity
x	location of the interface
Y_0	zero-order Bessel function of the second kind

Greek symbols

α	thermal diffusivity
β	liquid fraction
γ	thermal expansion coefficient
ε	discrepancy
θ	dimensionless temperature
μ	dynamic viscosity
ρ	density
σ	standard deviations
τ	time

Superscripts

–	dimensionless
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Subscripts

ave	averaged values
exp	experimentally obtained values
i, j	dimension vectors
num	numerically obtained values
ref	reference

solid and liquid phases as well as other thermal properties. The thermal conductivity of the sample was evaluated from the comparison of time-temperature graphs between the specimen and the reference material. Zhang et al. [16] investigated thermal conductivity of phase change material slurry using conventional transient hot wire method during the melting process. Measurement error induced by latent heat releasing during the phase change was corrected numerically and a more accurate value of the slurry's thermal conductivity was obtained. Connor et al. [17] proposed the best path prediction (BPP) method to obtain the thermal properties of organic PCM in liquid state near the melting point. This method determines which of tens of thousands of combinations of 22 different available theoretical techniques provides best agreement with thermal diffusivity values based on reported values, and results shown deviation are within 15% for organic PCMs.

Due to the low thermal conductivity of the PCMs, typically in the range of 0.15–1.0 W/m K [18], substantial and sustained heat treatment is usually applied to the specimen in most conventional measurement techniques. However, this imposed heat treatment may alter the crystal form of the specimen and thereby influence the thermal conduction behavior of the sample, since the thermal properties of the PCM are dependent upon the local temperature. Furthermore, the temperature variation range of the PCMs during energy charging/discharging processes is usually near the corresponding melting temperature of such materials. As a result, it is important to note that the data of the thermal conductivity should be characterized under relevant temperature range. Among studies relating to this aspect, Zhou et al. [19,20] assumed the solid-liquid interface as the heat transfer surface on the basis of one-dimensional Neumann model, and thermal conductivity of the PCMs were experimentally determined. However, their experimental rig could not reliably provide the ideal linear temperature field with coordinate system, and errors were induced by the unsatisfactorily linearized temperature field.

This paper demonstrates a dynamic measurement technique to determine the liquid phase thermal conductivity of PCM near the melting point. First, a measurement model was developed based on the constrained cylindrical inward melting problem under Stefan conditions. Then, well-controlled and well-characterized experimental measurements were performed, and the experiment results in terms of instantaneous interface locations and the ther-

mal conductivity for two kinds of inorganic PCM were reported. Furthermore, the factors that influence the measurement results were systematically analyzed and a numerical correction method was carried out to improve the measurement accuracy as well.

2. Measurement model development

Consider a cylinder filled with homogeneous solid state PCM in Fig. 1. We suppose that the cylinder has a very large aspect ratio and consistent cross-sectional shape. The entire solid state PCM is initially kept at its melting temperature T_m . At a certain instance, the wall temperature of the cylinder is increased instantaneously to temperature T_0 , which is slightly higher than T_m , and is kept steady. Consequently, the solid at the peripheral of the cylinder starts to thaw and the liquid-solid interface moves inward as time elapses, while the temperature in the solid state PCM remains at the melting temperature T_m still, meaning the heat transfer in the solid region is negligible. We assume that the sensible heat of the materials is neglected and the heat flow is transferred by

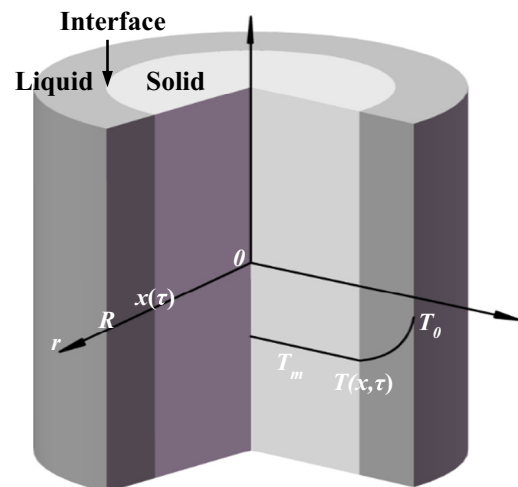


Fig. 1. Schematics of the cylindrical inward melting process under Stefan boundary.

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