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Theoretical analysis of novel device for measuring the thermal conductivity of liquids ☆

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Abstract

This paper aims to propose a novel design of microdevice for measuring the thermal conductivity of a liquid drop with a few volumes. The microdevice consists of a thin film that covers a cavity of the substrate. The thin film has a circular centered heater and several temperature sensors that are located at different radial locations from the heater. Once a known voltage is applied to the heater, the thermal conductivity of liquid drop that spreads over the heater and the temperature sensors can be determined from the measured temperature responses at different radial locations. This study provides theoretical predictions of temperature responses that are obtained from the diffusion equation of a semi-infinite cylindrical model. With an uncertainty in temperature measurement of 0.1 K, the uncertainty in determining the nominal thermal conductivity of 0.3 W/m-K is less than 0.3%.

Keywords: Thermal conductivity; Liquids; Microdevice

1. Introduction

Numerous methods have been proposed on the measurement of the thermal conductivity of liquids under different ranges of temperature and pressure over the past several decades. Large numbers of measured data were published. These measured methods can be classified into two types [1]; namely, steady-state and unsteady-state methods. The steady-state methods are well developed, but are expensive in equipment and are practically difficult in operation. Among various unsteady-state methods are presented so far, a transient hot-wire method becomes one of commonly used techniques for the measurement of the thermal conductivity of liquids [2]. The question is that the transient hot-wire method usually needs large volumes of liquid for measuring. However, some of the liquids are very expensive and are not easy obtained such as nano-fluids, magnetic nano-fluids, and medical drugs. The purpose of this study is to design a novel microdevice for the measurement of thermal conductivity of liquids, which needs small volume of liquid and takes a short period of time. This microdevice has a suspended thin film that covers a cavity of substrate. A liquid drop spreads over the thin film that has a circular centered heater and several temperature sensors at different radial locations from the centered heater. Once an applied heating power is suddenly applied to the microheater, the radial distributions of temperature response on the thin film surface will be used to determine the thermal conductivity of

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Nomenclature

a	Radius of microheater
c_{p}	Specific heat
q	Heat flux
t	Time
A	Function defined in Eq. (8)
C_i	Function defined in Eq. (15)
T	Temperature
b	Radius of cylinder
k	Thermal conductivity of liquid
r	Radial coordinate
z	Axial coordinate
B_i	Function defined in Eq. (9)
D	Function defined in Eq. (16)
T_{i}	Initial temperature

Greek symbols

α	Thermal diffusivity
ρ	Density
λ_i	Eigenvalue
θ	Dimensionless form of temperature

Superscript

*	Dimensionless form of properties

liquid if most heat is transported into the microheater into the liquid. Apparently, this proposed approach belongs to the category of unsteady-state approach.

To obtain the temperature responses in liquid drop, one needs to solve the diffusion equation of a semi-infinite cylinder. The air in the cavity can be regarded as thermal insulator. Therefore, Green's function of the diffusion equation for the microdevice can be obtained. An introduction to the use of Green's function method for solving heat conduction problems is presented by Carslaw and Jaeger [3]. They derived the relevant Green's function by using Laplace transform. Ozisik [4] describes the use and advantages of Green's function method, and derives some of the functions by the separation-of-variables method. Using Green's function solution to solve heat conduction problems has several advantages. First, a systematic procedure is available for obtaining the Green's function solution. Once these functions are obtained and tabulated, they may be used without any effort spent on the details of their derivation. Second, the one dimensional Green's function solution may be used as making blocks to achieve two and three dimensional solutions to suitable problems. The specifics of the multiplication process to obtain two- and three-dimensional solutions are presented by Beck [5]. Books by Greenberg [6] and Beck et al. [7] expose the usefulness of the Green's function method.

The purpose of this study is to design a novel device for measuring the thermal conductivity of liquids, which only needs few liquids. A droplet of test liquid is dripped on the device and the temperature filed of liquid is solved using Green's function method. The theoretical analysis of the novel device for measuring the thermal conductivity of liquids is presented in this study.

2. Mathematical model

The novel microdevice for measuring thermal conductivity of liquids is shown as Fig. 1. The bottom of the microdevice is silicon, and the top is poly-silicon with one heater at the center and several sensors distributed radially. The microdevice consists of a thin film that covers a cavity of the substrate to prevent heat loss. The problem