

Measurement of thermal properties of microfluidic samples using laser point heating thermometry

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Abstract

This work introduces a novel method to measure the thermal conductivity, diffusivity, and heat capacity of a microfluidic sample having a small-volume of the order of 1 μl . The method is based on a new concept named laser point heating thermometry (LPHT). The method employs point heating of a thermocouple tip using a focused laser beam. As the suggested scheme utilizes external optical heating of a temperature probe, a relatively large amount of heat can be generated at a localized spot. Furthermore, the temperature of the heated spot can be effectively monitored from thermoelectric potential without undesirable electrical interference in the heating and sensing circuitry. In addition to the thermal-property measurement, this simultaneous point heating and point sensing technique can be employed in a variety of thermal-sensing applications including velocity and motion measurement.

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1. Introduction

Thermal properties such as thermal conductivity, diffusivity and heat capacity are fundamental in engineering systems that involve heat transfer as well as in scientific studies. Particularly, the need for thermal analysis of a microfluidic sample is rapidly growing as liquid samples of tiny volume are frequently used in microfluidics and bioengineering applications [1–3]. In this regard, this work proposes a novel method to measure thermal transport properties of a small-volume fluid sample in the microliter range. Numerous schemes have so far been developed to measure the thermal properties of fluids. Among them, the transient hot-wire method is regarded as one of the most standard techniques to determine the thermal conductivity and diffusivity of a fluid sample [4]. In the transient hot-wire method, a thin metallic wire typically several centimeters in length is immersed in the sample fluid and electrically heated by Joule heating while the resistance variation monitors the thermal response. Accordingly, the method requires a sample volume at least hundreds of milliliters, which is often unallowable for expensive bio-samples and functional materials. It is also obvious that microfluidic applications necessitate thermal analysis

of microfluidic samples as they constantly pursue integration of multiple functionalities on a single substrate having a small dimension.

Measurements of thermal conductivity and diffusivity require two main elements: heating and sensing (thermometry). As the thermal penetration depth $\sim \sqrt{\alpha t}$ (α : thermal diffusivity, t : time) is generally small compared to the dimension of the heating element, conventional measurement schemes cannot be applied to a small sample volume because the majority of the supplied heat is consumed for heating up the heating/sensing element, not the sample. It is thus apparent that a method based on point heating and point sensing (PHPS) principle is the most ideal for local property measurement. Recently, a microcalorimetric technique using the Peltier effect, which relies on the PHPS principle, has been suggested [5]. In the method, a thermocouple (TC) tip serves as a PHPS element. However, in the case of the Peltier sensor, both heating and sensing are based on the same physical principle, i.e. thermoelectric effect. The method therefore has intrinsic interference between heating and sensing signals. To avoid the interference, the heater and sensor should be either spatially or temporally separated, which often makes *in situ* monitoring of the thermal response of a heating element at the same location impossible, resulting in difficulties in data analysis.

In this work, a novel method entitled the laser point heating thermometry (LPHT) is proposed to measure the thermal con-

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ductivity and diffusivity of a microfluidic fluid sample. The key to the technique is optical point heating of a tiny thermometer, for example a thermocouple tip. Consequently, a small fluid element can be selectively heated with simultaneous monitoring of the thermal response. The experiment employs a focused laser beam to heat a microthermocouple tip and the real-time temperature response is detected by the Seebeck voltage signal from the junction. A multiparameter-fitting scheme is utilized to simultaneously determine the thermal conductivity, and diffusivity.

2. Theory

2.1. Heat conduction

Fig. 1 shows the principle of the LPHT technique schematically. As the TC tip generally has a much greater conductivity than the fluid, uniform temperature distribution in the TC tip can be assumed. In addition, if the heat loss through the TC wires is negligible, the temperature of the TC can be expressed analytically as [6]:

$$T = \frac{q}{4\pi ak} \left\{ \frac{1 + ac_1}{c_1} - \frac{2a^2 c_1^2 c_2^2}{\pi} \times \int_0^\infty \frac{e^{-\alpha u^2 t/a^2}}{[u^2(1 + ac_1) - ac_1 c_2]^2 + [u^3 - uac_1 c_2]^2} du \right\} \quad (1)$$

and

$$c_1 = \frac{h}{k}, \quad c_2 = \frac{4\pi a^3 \rho C}{M_s C_s}$$

where a , C_s , and M_s are the size, heat capacity, and mass of the TC tip, respectively, and C , k and ρ are the heat capacity, thermal conductivity and density of the fluid sample, respectively (q : heat transfer rate, h : contact thermal conductance at the TC tip–fluid interface).

The above equation provides a simple analytical tool to determine the thermophysical properties of the liquid sample. However, analysis of the rigorous temperature field indicates that the heat loss through the TC wire significantly deteriorates

the accuracy, up to about 20%. Therefore, our suggested scheme uses the full numerical solution to the heat conduction problem, considering heat conduction in the TC tip and wires. An FEM (finite element method) scheme is employed to obtain the numerical solution, assuming the convective heat transfer in the liquid is negligible. The temperature field taking the heat conduction loss through the TC wire is displayed in Fig. 2. Comparison of the results in Fig. 2(a) with those in Fig. 2(b) manifests that heat conduction through the wires substantially modifies the temperature field and therefore the numerical procedure is necessary to determine the thermal properties.

2.2. Thermal-property determination

Since the amount of heat flow cannot be quantified precisely in an optical-heating method such as this work, the temperature is normalized by the maximum value at a reference time t_f :

$$\Theta(t) = \frac{T(t)}{T(t_f)} \quad (2)$$

If the size and heat capacity of the TC tip are known, the temporal variation of the normalized temperature becomes a function of thermal conductivity and thermal diffusivity only. Therefore, the normalized transient temperature together with a multiparameter-fitting algorithm yields the properties. Determination of the tip size using a microscope is possible but may cause random error because of the non-uniformity in the shape of a commercial TC tip. The exact value of the heat capacity is also unknown. Therefore, the fitting parameters include the size and heat capacity of the tip. The difference function F between the theoretical and experimental temperature data (Θ_n^{the} and Θ_n^{exp}) is thus minimized numerically:

$$F(k, \alpha, \dots) = \sum_{n=1}^N (\Theta_n^{\text{the}} - \Theta_n^{\text{exp}})^2 \quad (3)$$

In the present study, the quadratic interpolation and the Powell's method were utilized as single-parameter and multiparameter optimization schemes, respectively [7].

Since the time scale of temperature variation is related to the sensitivity of thermal-property measurement, it is important to determine the heating-pulse duration t_f properly. Fig. 3 shows the measurement sensitivity as a function of the pulse duration for three different thermal conductivity values. The sensitivity can be expressed as:

$$S = \frac{1}{E} \frac{dE}{dk}, \quad E = \sum_{n=1}^N (\Theta_n)^2 \quad (4)$$

Based on the sensitivity analysis in the range of the thermal conductivity of typical liquids 0.05–0.6 W m^{−1} K^{−1}, the pulse duration was determined to be 50 ms.

3. Experiment

Fig. 4 displays the schematic diagram of the experimental setup. An Ar⁺ ion laser is used as a heat source. The temporal

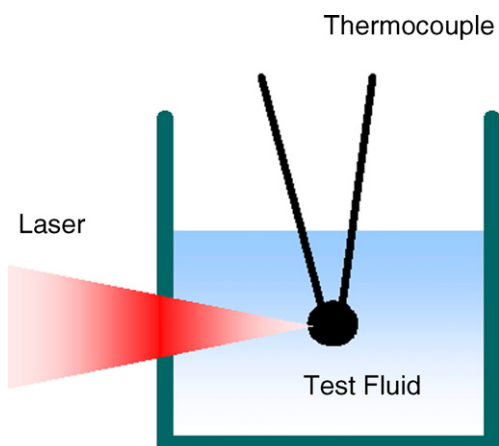


Fig. 1. Principle of the LPHT technique.

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