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Adaptable thermal conductivity characterization of microporous membranes based on freestanding sensor-based 3ω technique

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ABSTRACT

Adaptable thermal conductivity measurements of microporous membranes based on freestanding sensor-based 3ω technique is proposed. The adaptability and flexibility of the freestanding sensor enable microporous membranes with various mechanical and thermal properties to be easily sandwiched between the freestanding sensor and a semi-infinite thermally conductive substrate, assembling into a five-layer substrate-membrane-sensor-membrane-substrate configuration. A theoretical model for the calculation of membrane's thermal conductivity is provided by comparing the temperature difference between the five-layer configuration and a three-layer substrate-sensor-substrate configuration. The well agreed experimental results with the theoretically calculated values indicate that the present strategy can be widely applied to the thermal properties characterization of microporous membranes in membrane distillation.

1. Introduction

In membrane distillation (MD), the accurate thermal conductivity measurements for the microporous membranes have attracted great interest as it determines the thermal efficiency η of the MD process [1–3]. In order to obtain the effective thermal conductivity of microporous membranes, several models have been exploited, such as parallel thermal resistance model, cascade thermal resistance model, and combination of both of them with a distribution factor, which takes into account the structural effects of the material [1,3,4]. Although the thermal resistance technique based on an improved Lees' disc apparatus for thermal conductivity characterization of several commercial membranes has been reported [4], the experimental techniques for measuring the thermal conductivity of microporous membranes has rarely been reported as the thickness of the microporous membranes is only about 100 μm, which cannot fulfill the experimental condition using conventional techniques. Therefore, exploring practical techniques for the accurate characterization of the thermal conductivity of microporous membranes with tens of micrometers thickness is urgently expected and needed.

A promising measurement technique for thermal conductivity named freestanding sensor-based 3ω technique has been pioneered in our previous work, and it has been demonstrated as a useful method for the bulk and wafer samples, which are applicable to the semi-infinite media assumption [5,6]. For the microporous membrane typically with low thermal conductivity, the thermal resistance introduced by the membrane when subject to harmonic thermal waves can be accurately indentified in a certain range of frequencies, providing the basis for the feasibility of this technique in membrane measurement. Moreover, different from the traditional 3ω technique [7,8], this modified technique exhibits higher accuracy and unique adaptability. On one hand, it is not necessary to deposit the electrodes on the samples for the measurement, thus effectively avoiding destruction to the microporous membranes. On the other hand, the flexible sensor enables excellent contact with the surface of microporous membranes with different morphology and roughness, thus effectively promoting the accuracy of the measurement. Therefore, it is rational to believe that this adaptable freestanding sensor-based 3ω technique can become a competent candidate for the thermal conductivity characterization of thermal insulating films, such as microporous membranes in MD applications. In this work, based on this adaptable technique stemming from the differential 3ω method [8–11], the thermal conductivity measurements of three kinds of microporous membranes are reported. Significantly, we deduced the theoretical model in the

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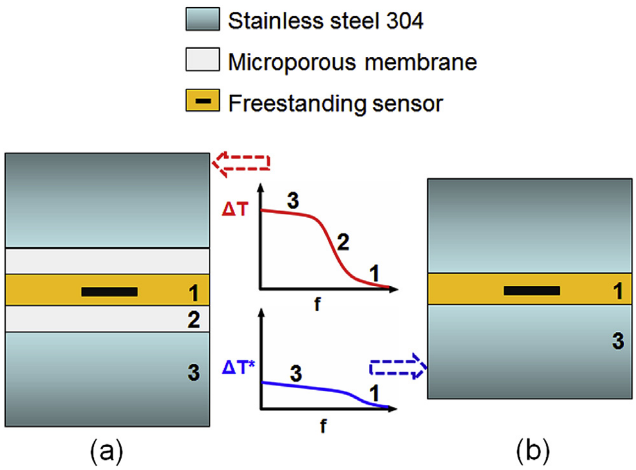

Fig. 1. Schematic diagram for (a) five-layer substrate-membrane-sensor-membrane-substrate characterization configuration, (b) three-layer substrate-sensor-substrate configuration as a control, and the temperature responses of the freestanding sensor at a wide range of frequencies.

symmetrical five-layer substrate-membrane-sensor-membrane-substrate system and investigated its applicability for thermal conductivity characterization of thermal insulation microporous membranes with tens of microns thickness. Furthermore, three factors in this measurement, the loading pressure, the thickness of membrane and the thermal contact resistance at adjacent interfaces, have been also investigated in detail.

2. Theory

It should be indicated that for the freestanding sensor-based 3ω technique the test structure can be regarded as a symmetrical three-layer configuration, sample-sensor-sample, when the sample (bulk and wafer) thickness is far larger than the thermal penetration depth [5,6]. However, for membrane specimens, which are typically tens of micrometers thick, the theoretical model is different from that for the bulk and wafer samples. In order to identify the thermal conductivity of the membrane, a symmetrical five-layer substrate-membrane-sensor-membrane-substrate system was built up, in which the membranes were symmetrically sandwiched between the freestanding sensor and substrates. Since the substrate is used for providing an isothermal boundary condition as well as flattening the membrane, we use the high thermally conductive materials, such as the stainless steel 304. The temperature responses in the symmetrical five-layer system and the symmetrical three-layer substrate-sensor-substrate system can be obtained, respectively (Fig. 1). According to the differential 3ω method, the difference in the temperature response between the two configurations should be attributed to the presence of the membranes. Therefore, the thermal conductivity of the membrane can be calculated by comparing the temperature difference between the two systems.

Based on our previous research [5,6], the solution of the complex temperature rise of the freestanding sensor for the symmetrical five-layer system can be described as a reduced form of the universal two-dimensional multilayer heat conduction formulation derived by Borca-Tasciuc et al. [11]

$$\Delta T = -\frac{p}{2\pi l k_{y,1}} \int_0^\infty \frac{1}{A_1 B_1} \frac{\sin^2(b\lambda)}{(b\lambda)^2} d\lambda, \tag{1}$$

where

$$A_{i-1} = \frac{A_i \frac{k_{y,i} B_i}{k_{y,i-1} B_{i-1}} - \tanh(\varphi_{i-1})}{1 - A_i \frac{k_{y,i} B_i}{k_{y,i-1} B_{i-1}} \tanh(\varphi_{i-1})}, \quad i = 2, 3 \tag{2}$$

$$B_i = \left(k_{xy,i}\lambda^2 + \frac{i2\omega}{\alpha_{y,i}}\right)^{1/2}, \quad i = 1, 2, 3 \tag{3}$$

$$\varphi_i = B_i d_i, \tag{4}$$

$$k_{xy,i} = k_{x,i}/k_{y,i}. \tag{5}$$

In the above expressions, subscript x, y corresponds to the in-plane and cross-plane directions, respectively. Subscript 1, 2, 3 corresponds to the Kapton film (the flexible insulating layer of the freestanding sensor), the membrane specimen and the substrate, respectively. p/l is the electrical power per unit length, k is the thermal conductivity, k_{xy} is the ratio of the in-plane to cross-plane thermal conductivity, b is the strip half width, λ is the integrating factor, ω is the angular frequency of the alternating current, α is the thermal diffusivity, and d is the thickness. As the substrate is semi-infinite, $A_3 = -1$ [11].

Similarly, the temperature rise of the freestanding sensor for the symmetrical three-layer system (marked by superscript *) is described as

$$\Delta T^* = -\frac{p}{2\pi l k_{y,1}} \int_0^\infty \frac{1}{A_1^* B_1} \frac{\sin^2(b\lambda)}{(b\lambda)^2} d\lambda, \tag{6}$$

$$A_1^* = \frac{A_3^* \frac{k_{y,3} B_3}{k_{y,1} B_1} - \tanh(\varphi_1)}{1 - A_3^* \frac{k_{y,3} B_3}{k_{y,1} B_1} \tanh(\varphi_1)}. \tag{7}$$

Here the semi-infinite substrate assumption is still valid, $A_3^* = -1$. Thus, the temperature difference between two systems is obtained as,

$$\Delta T - \Delta T^* = -\frac{p}{2\pi l k_{y,1}} \int_0^\infty \frac{1}{B_1} \left(\frac{1}{A_1} - \frac{1}{A_1^*}\right) \frac{\sin^2(b\lambda)}{(b\lambda)^2} d\lambda, \tag{8}$$

A detailed derivation of $((1/A_1) - (1/A_1^*))$ was listed in the Supplementary materials (See supplementary material for detailed derivation of temperature difference between two test systems). And the final expression is,

$$\frac{1}{A_1} - \frac{1}{A_1^*} = \frac{\tanh(\varphi_2)\left[1 - \tanh^2(\varphi_1)\right]\left(-\frac{k_{y,3}^2 B_3^2}{k_{y,2} B_2 k_{y,1} B_1} + \frac{k_{y,2} B_2}{k_{y,1} B_1}\right)}{\left[\frac{k_{y,3} B_3}{k_{y,1} B_1} + \frac{k_{y,2} B_2}{k_{y,1} B_1}\tanh(\varphi_2) + \tanh(\varphi_1) + \frac{k_{y,3} B_3}{k_{y,2} B_2}\tanh(\varphi_1)\tanh(\varphi_2)\right] \times \left[\frac{k_{y,3} B_3}{k_{y,1} B_1} + \tanh(\varphi_1)\right]}, \tag{9}$$