Algorithms for thermal diffusivity measurement of heterogeneous 1D materials based on Infrared Microscopy Enhanced Angstrom Method

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Abstract. An infrared microscopy enhanced Angstrom method has been developed to measure the thermal diffusivity. Infrared microscopy technique can acquire temperatures of multiple points at one shot. Two algorithms for calculating thermal diffusivity were proposed and compared in practice. One is based on global temperature data and the other is based on local temperature data. The calculated thermal diffusivities are denoted as \( \alpha_{\text{g}} \) and \( \alpha_{\text{l}} \). Three 1D materials of different heterogeneity (Cu wire, Ni-Cu wire and PVA-CNT fiber) were measured on the experimental platform. The calculated \( \alpha_{\text{g}} \) and \( \alpha_{\text{l}} \) values show that for homogeneous material such as Cu, these two algorithms give similar results, while for heterogeneous ones (Ni-Cu and PVA-CNT), they come to be discrepant. The data fluctuation analysis of \( \alpha_{\text{l}} \) zooms in the discrepancy and verifies that \( \alpha_{\text{l}} \) is more sensitive to local property change and more competent in revealing heterogeneous properties.

1. Introduction
The Angstrom’s method has been widely used for measuring the thermal diffusivity of materials [1-3]. Thermal diffusivities of materials such as copper, carbon fibers, carbon nanotubes and other materials have been measured by Angstrom method [4-6]. This method should lead to many local details missing for heterogeneous material. Other traditional methods such as laser flash method, T-type method [7-8] have the same trouble. T-type method read current and voltage signals. Laser flash method cannot measure temperature of multiple points due to the limitation of experimental setup. This work introduces a new measurement technique to measure thermal diffusivity based on infrared (IR) camera enhanced Angstrom method. The large area temperature data can be acquire by the IR camera at one shot. This method overcomes the averaging issue that bothering all the traditional methods mentioned above. Two algorithms for calculating thermal diffusivity have been developed on basis of IR Microscopy measurement technique. The data fluctuation analysis provide an evaluation method for the heterogeneity of 1D material.

2. Methodology

2.1. Theory of thermal diffusivity measurement
Thermal diffusivity can be derived by Angstrom method. Considering 1D heat transfer diffusion with heat loss, the equation can be expressed as follow [1]. where \( \alpha \) is thermal diffusivity, \( T \) is the temperature...
[K], $t$ is the time [s], $X$ is the position, and $m$ is the coefficient of surface heat loss.

$$\frac{1}{\alpha} \frac{\partial T}{\partial t} + m^2 T = \frac{\partial^2 T}{\partial x^2}$$

(1)

The schematic diagrams of Angstrom method are shown in Figure 1. A sinusoidal heat wave is loaded to one end of the sample at $S$ position. Then temperature at position $X_1$ and $X_2$ also show the sinusoidal feature. By solving Eq. (1), the thermal diffusivity can be obtained as follow [2]:

$$\alpha = \frac{L^2}{2 \cdot dt \cdot \ln \left( \frac{A_2}{A_1} \right)}$$

(2)

where $L$ is the distance between position $X_1$ and $X_2$; $A_1$ and $A_2$ is the amplitude of the temperature waves at $X_1$ and $X_2$; $dt$ is the phase delay between the waves at $X_1$ and $X_2$.

2.2. Experimental test platform

Figure 2a shows the experimental test platform. The set-up is composed of signal generator, thermoelectric module (TE) model, heat sink, Infrared (IR) camera, sample, vacuum champer and personal computer (PC). A sinusoidal current signal is generated by the Signal generator. The current signal is passed to the TE model, which is heated to generate a sinusoidal heat wave. One end of the sample is in contact with the TE model and the other end is fixed onto the heat sink. The vacuum champer can decreases convective heat loss. Thus, The sample, heat sink and TE module are placed into the vacuum champer. The sinusoidal heat wave is provided by the TE module. The real-time temperature data are read by IR camera. The picture indicated by an arrow in Figure 2a displays one as-collected image during the measurement. Figure 2a shows fifteen collecting points along the sample and Figure 2b gives their time profiles.

2.3. Algorithms of Angstrom method based on Infrared Microscopy

Infrared Microscopy enhanced Angstrom method can simultaneously read temperature of multiple points. Here we pick $n$ segments ($n+1$ points) and employ two algorithms for thermal diffusivity.
calculation. The major difference between them is the definition of $L$. Figure 3 presents the details. Accordingly, we have two expressions for thermal diffusivity calculation,

$$a_n^G = \frac{L_n^G}{2 \cdot dt \cdot \ln \left( \frac{A_n}{A_{n-1}} \right)} \quad \text{and} \quad a_n^L = \frac{L_n^L}{2 \cdot dt \cdot \ln \left( \frac{A_n}{A_{n+1}} \right)}$$

(3)

In general, the thermal properties in any part of 1D homogeneous materials should be the same, while that of 1D heterogeneous materials may be discrepant. Hence $a_n^G$ and $a_n^L$ can be used as the basis for heterogeneity judging.

3. Findings

3.1. Thermal diffusivity of heterogeneous 1D materials

In the experiment, a Cu wire, a Ni-Cu wire and a PVA-CNT fibre were picked for the comparison measurement of $a_n^G$ and $a_n^L$. Figure 4 shows the calculated $a_n^G$ and $a_n^L$ of three materials. In Figure 4a, the change trends of $a_n^G$ and $a_n^L$ for the Cu wire are the same. When $n=2$, there is a slight difference between them, which may be caused by experimental error. In Figure 4b, the change trends of $a_n^G$ and $a_n^L$ for the Ni-Cu wire and PVA-CNT fibre are quite different. The change of $a_n^G$ is small, which makes the $a_n^G$ almost a stable value, while on contrast, $a_n^L$ shows evident fluctuations around $a_n^G$.

$$L_n^G = x_n - x_1$$

$$L_n^L = x_{n+1} - x_n$$

Figure 3. (a) and (b) are schematic diagrams of $L_n^G$ and $L_n^L$.

Figure 4. $a_n^G$, $a_n^L$ obtained by Infrared Microscopy enhanced Angstrom method.

$a_n^G$ is the thermal diffusivity of the entire sample, representing an average value. It is a manifestation of overall thermal performance. $a_n^L$ is the location thermal diffusivity at certain point of the sample. For homogeneous materials, thermal properties are invariable at any position. Then $a_n^G$ and $a_n^L$ should be same. That is what we have observed in Figure 4a. But for heterogeneous materials such as composites, $a_n^G$ should be different with $a_n^L$ showing more dramatic fluctuation due to the uneven mixing of substances and inconsistent molecular ordering. This is what happens in Figure 4b. The difference between them can be used to evaluate the degree of heterogeneity of 1D material. The suggested quantification details are provided below.

3.2. Fluctuation analysis

To distinguish the fluctuation origins, whether it is from the experimental error or from the heterogeneity of materials, the data analysis should be designed. As mentioned before, the algorithm of $a_n^G$ has an
averaging effect over the length under test. Thus its relative fluctuation \( f_n^{G} \) (Eq. (4)) renders more experimental error.

\[
\bar{\alpha} = \frac{\alpha_1^G + \alpha_2^G + \cdots + \alpha_n^G}{n}, \quad f_n^{G} = \frac{abs(\alpha_n^G - \bar{\alpha})}{\bar{\alpha}} \tag{4}
\]

On contrast, \( \alpha_k^L \) is the local thermal diffusivity of each segment. Its average value (\( \bar{\alpha}^{L} \)) is the true average of the entire sample. It fluctuates more drastically than \( \alpha_n^G \) when the sample is heterogeneous, thus its relative fluctuation \( f_n^{L} \) (Eq. (5)) renders more heterogeneity information.

\[
\bar{\alpha} = \frac{\alpha_1^L + \alpha_2^L + \cdots + \alpha_n^L}{n}, \quad f_n^{L} = \frac{abs(\alpha_n^L - \bar{\alpha})}{\bar{\alpha}} \tag{5}
\]

Figure 5 exhibits their comparison. For homogeneous material Cu, the two algorithms of relative fluctuation give no big difference. Thus its standard deviation of the fluctuation from the local algorithm (\( \sigma_{homo}(f) \)) can be used as a benchmark for experimental error, only the \( n=1 \) data should be crossed out due to obvious deviation, which may be caused by system error. For heterogeneous material Ni-Cu and PVA-CNT, the error origin and hetero-origin are mixed and both of them contributed to the apparent standard deviation (\( \sigma_{hetero}(f) \)). Thus the heterogeneity \( h \) hidden in the drastic fluctuations of \( f_n^{L} \) should be defined as \( h = \sigma_{hetero}(f) - \sigma_{homo}(f) \). And for Ni-Cu, \( h=0.0273 \), while for PVA-CNT, \( h=0.1148 \).

![Figure 5. Schematic diagram of errors the \( f_n^{G} \) (a) and \( f_n^{L} \) (b)](image)

4. Conclusion
The use of Infrared Microscopy temperature measurement can directly measure and read temperature of multiple points on 1D sample under test. Two algorithms of 1D material thermal diffusivity measurement are developed based on the multiple points’ temperature acquisition. One is based on global temperature data and the other is based on local temperature data. The according calculated thermal diffusivities are denoted as \( \alpha_n^G \) and \( \alpha_n^L \). The measured thermal diffusivities of Cu, Ni-Cu and PVA-CNT and data fluctuations were discussed. \( \alpha_n^G \) and \( \alpha_n^L \) of Cu are almost the same, while there are obvious differences between \( \alpha_n^G \) and \( \alpha_n^L \) of Ni-Cu and PVA-CNT. In addition, the error-origin and the hetero-origin for the fluctuations were distinguished by designed data analysis and the heterogeneity \( h \) is defined accordingly.

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